Wayne State University
College of Liberal Arts & Sciences
Department of Physics and Astronomy

ALICE Status

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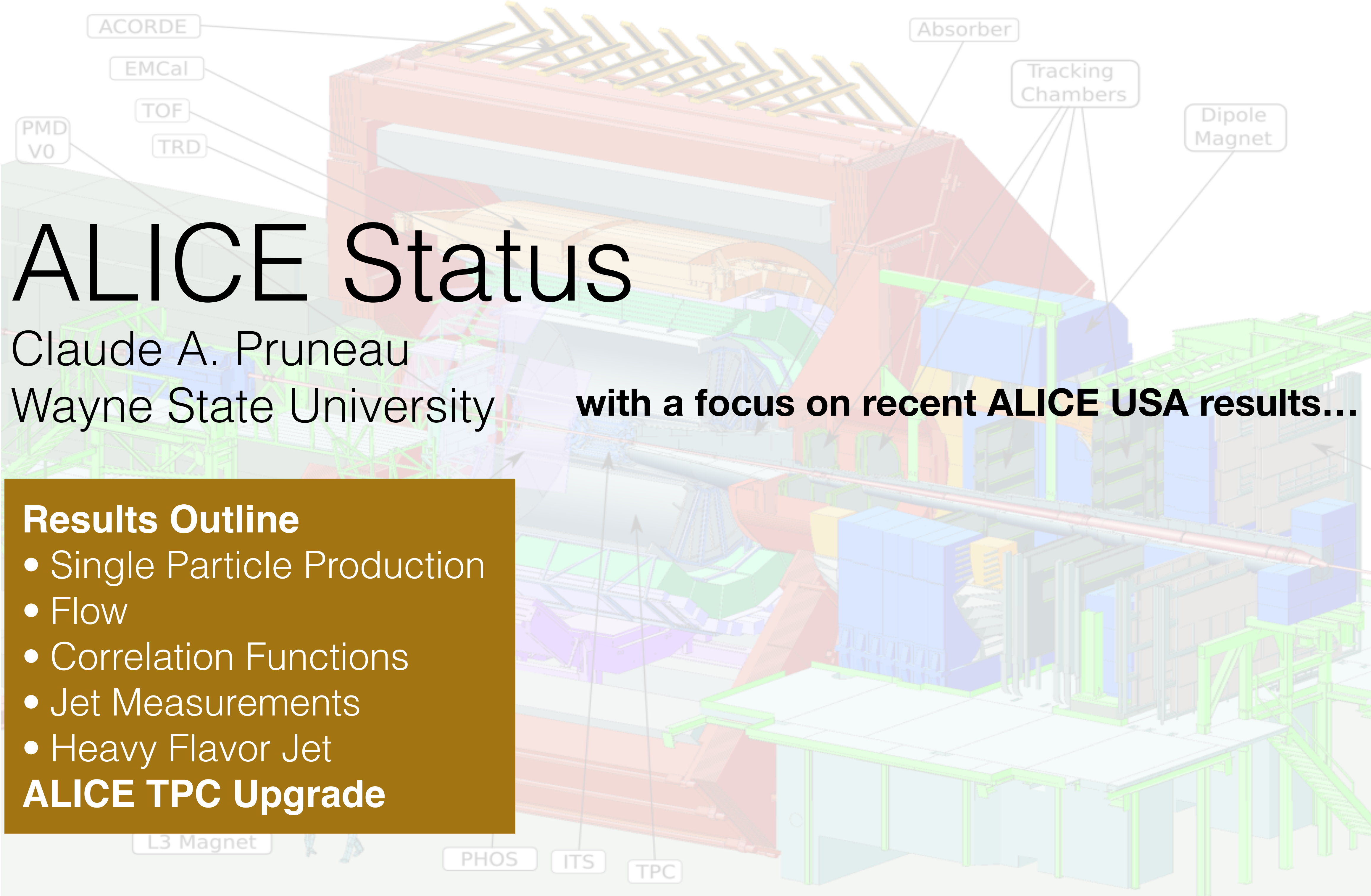
Wayne State University

with a focus on recent ALICE USA results…



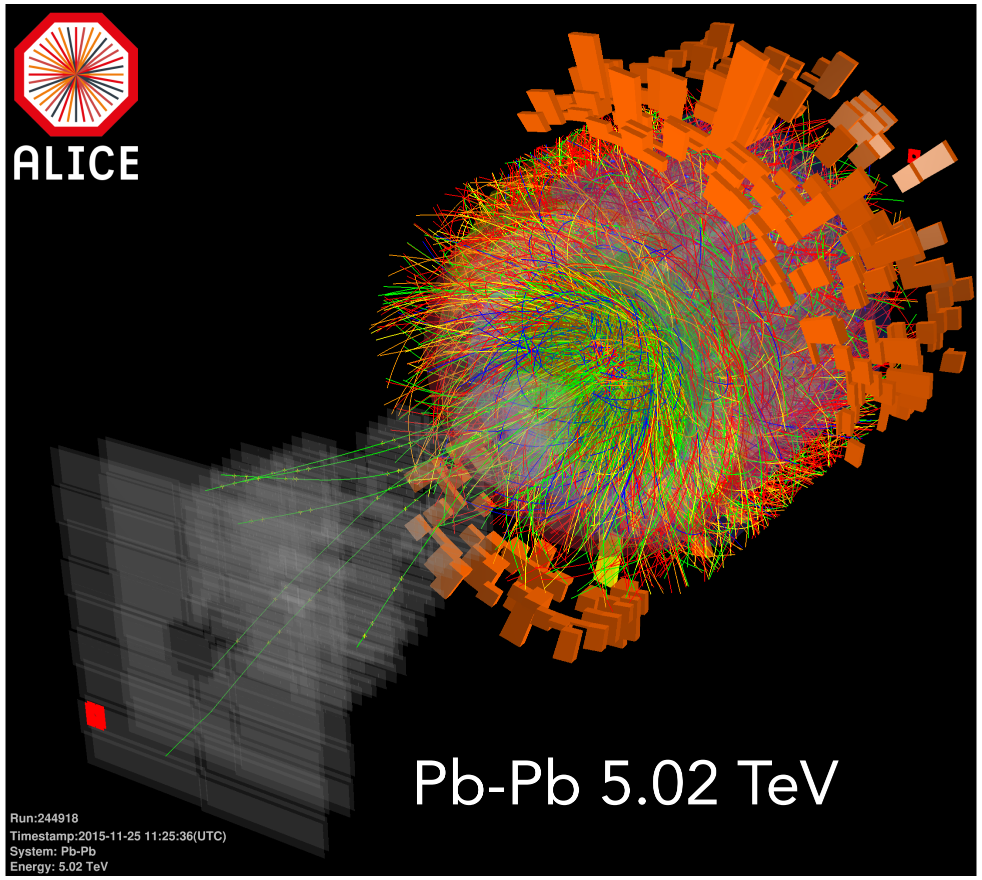
Results Outline

- Single Particle Production
- Flow
- Correlation Functions
- Jet Measurements
- Heavy Flavor Jet

ALICE TPC Upgrade

Eight years of data taking…

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	*5.02*	*~1 nb^{-1}*
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}



LHC Run 2 data analysis is in full swing.
Significant increase in integrated luminosity in pp, p-Pb, and Pb-Pb collisions allows more and more precise investigation of statistics hungry probes.

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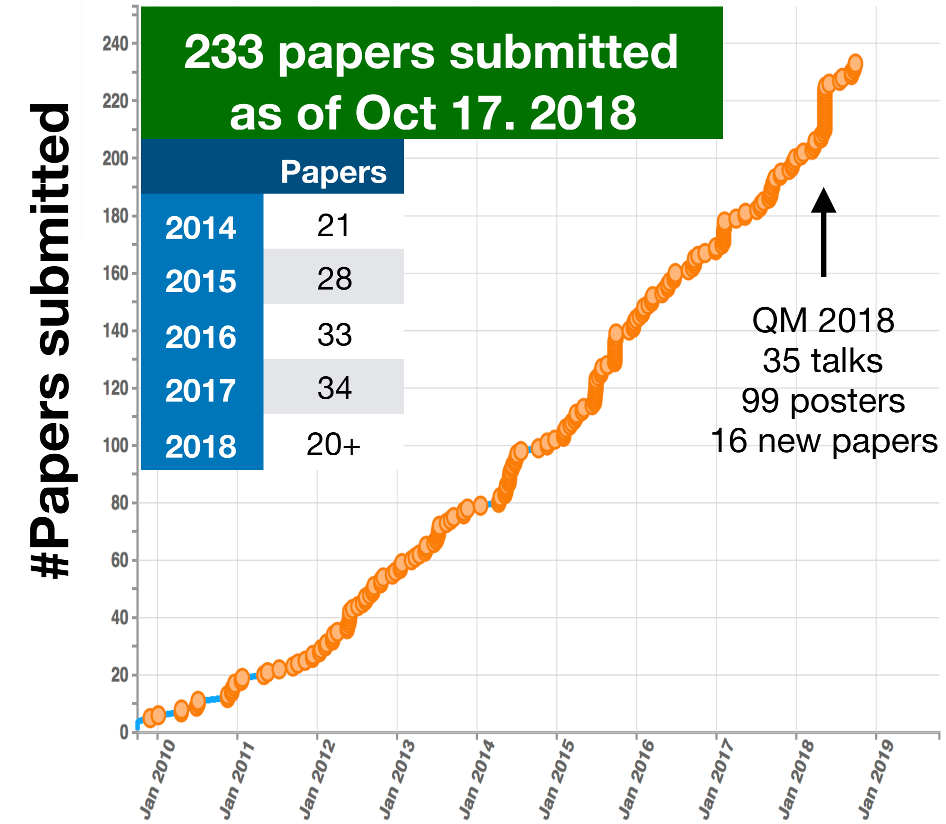

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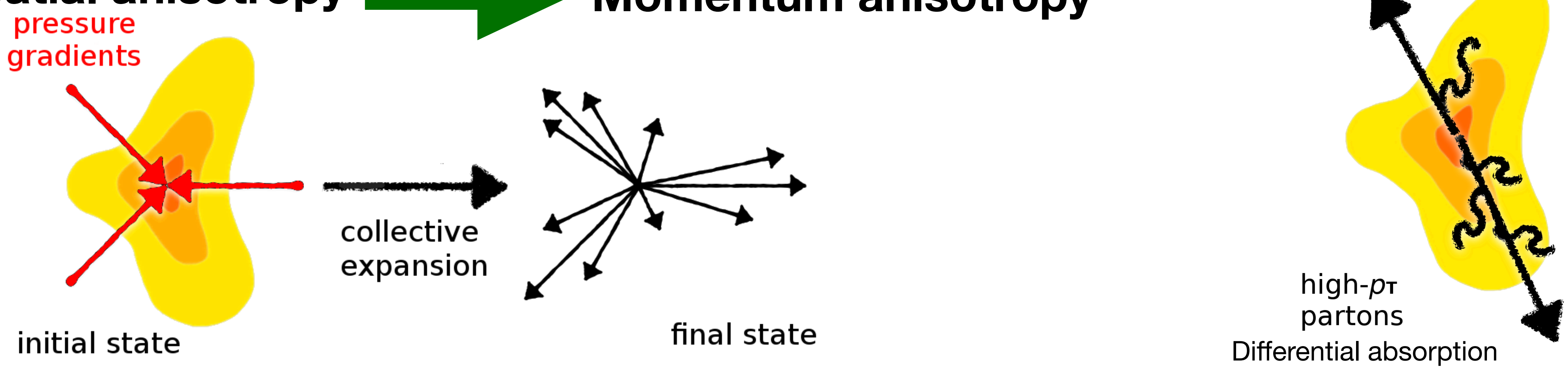
Working Groups:
- CF:Correlations Fluctuations Bulk
- DQ: Dileptons and Quarkonia
- HF: Heavy Flavor
- GA: photon and pion working group
- LF: Light Flavor Spectra
- JE: Jets
- UD: Ultraperipheral/Diffractive

QCD at High Temperature: Quark Gluon Plasma (QGP)

- **Proof of existence**
- **Properties**
  - Nature of phases (DoF) & transitions (1st, 2nd order, cross-over)?
  - Equation of state (EoS)
  - **Shear & Bulk Viscosity**
  - Electrical/Thermal conductivities
  - Heat Capacity (?!)
  - Compressibility (?!)
  - Hadrochemistry
  - Transport Properties (dE/dx)
- **Technical Questions**
  - **A+A Initial conditions**
  - System size/lifetime
  - **QGP or flow in Small systems vs. large systems?**
  - Understanding hadronization
- **New states of matter**
  - Chiral Magnetic Effect (CME)
  - Disoriented Chiral Condensate (DCC)
- **Tools**
  - Correlation Functions, Flow
  - Jets
  - Heavy Flavor
  - …

What is flow?

Spatial anisotropy → **Momentum anisotropy**



Momentum anisotropy: $$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]$$

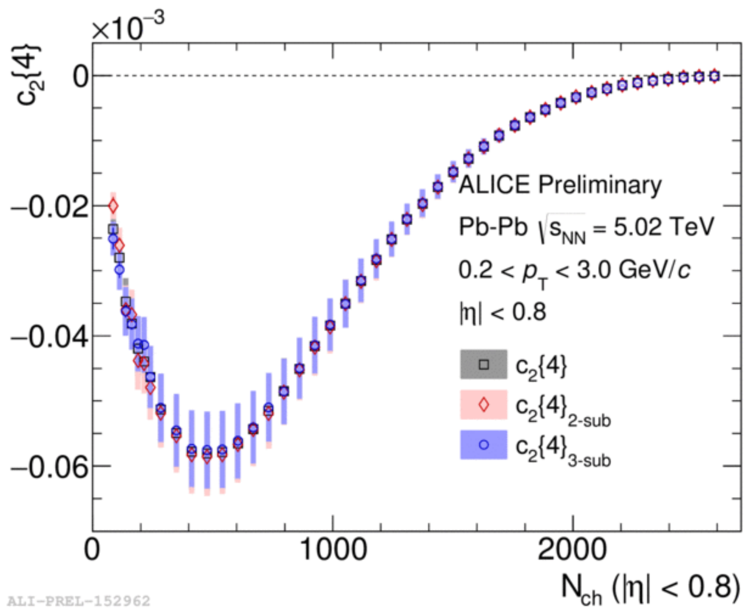
- **Collective particle momentum anisotropies in the transverse plane** quantified by **coefficients v_n**
  - **Soft sector** (pT< 2 GeV/c): multiple interactions between partons (collective) **convert initial-state (IS) spatial anisotropy into final-state momentum anisotropy**,
  - **Hard sector** (pT > 10 GeV/c): **path-length dependent parton energy-loss produces final-state anisotropy,**
- **Common origin**: **Spatial anisotropies** determined by **initial geometry of the collision, including IS fluctuations**

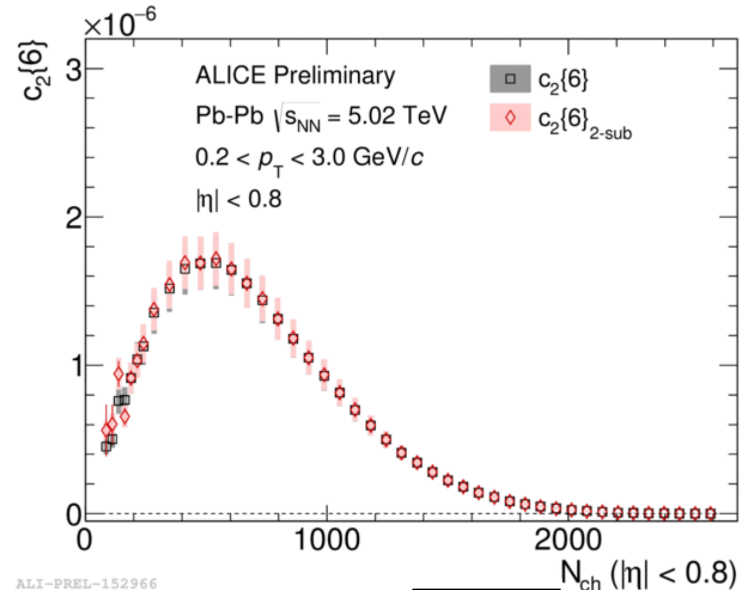
- **Toolset**:
  - Two-particle cumulants
  - **Multi-particle cumulants**
    - Generic framework[1]
  - **Scalar Product (SP) method**
  - **Symmetric Cumulants (SC)**
    - Decomposition of **linear and non-linear contributions** to flow.

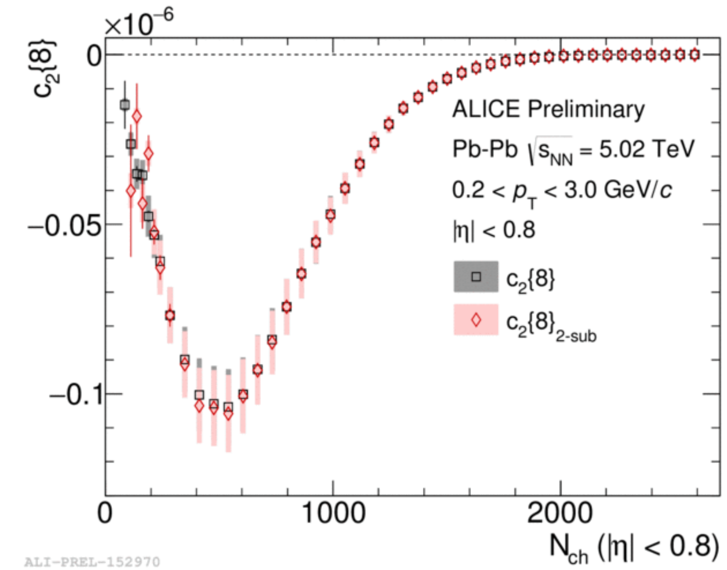
[1]A. Bilandzic et al., Phys. Rev. C 89, 064904 (2014)

Collectivity in AA

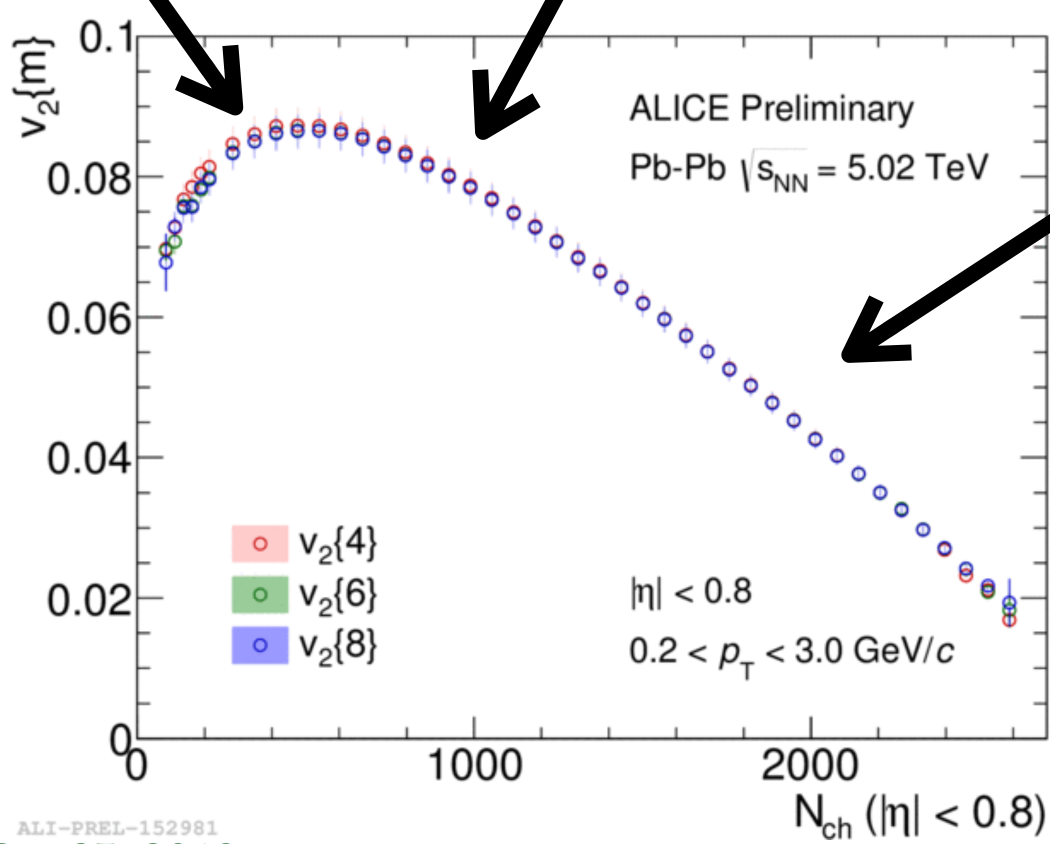
Are Correlations long-range & involving multiple particles?







$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$ $\quad v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$ $\quad v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$



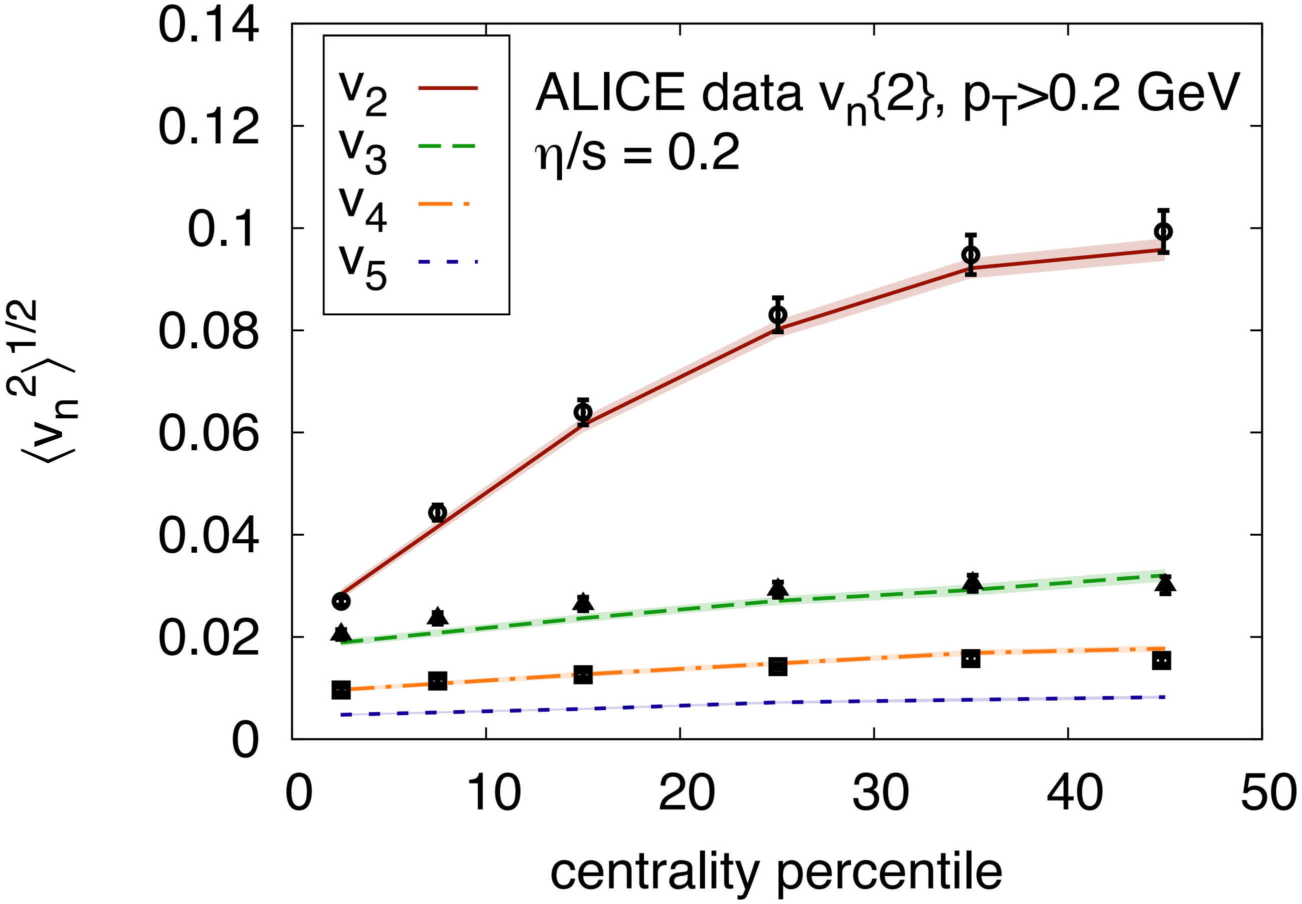
$v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

Long range collectivity in Pb-Pb

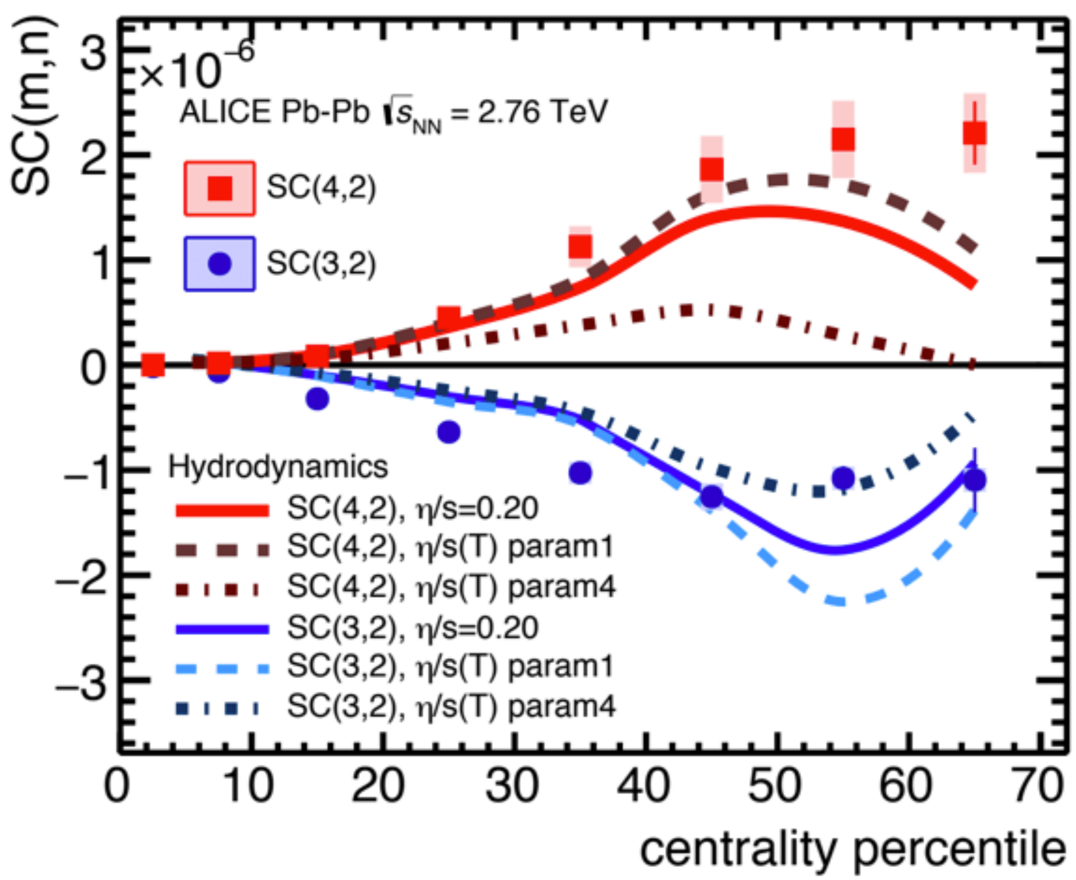
Origin of Collectivity in Pb—Pb?!

ALICE, PRL 107, 032301 (2011)

C. Gale et al PRL 110, 012302 (2013)



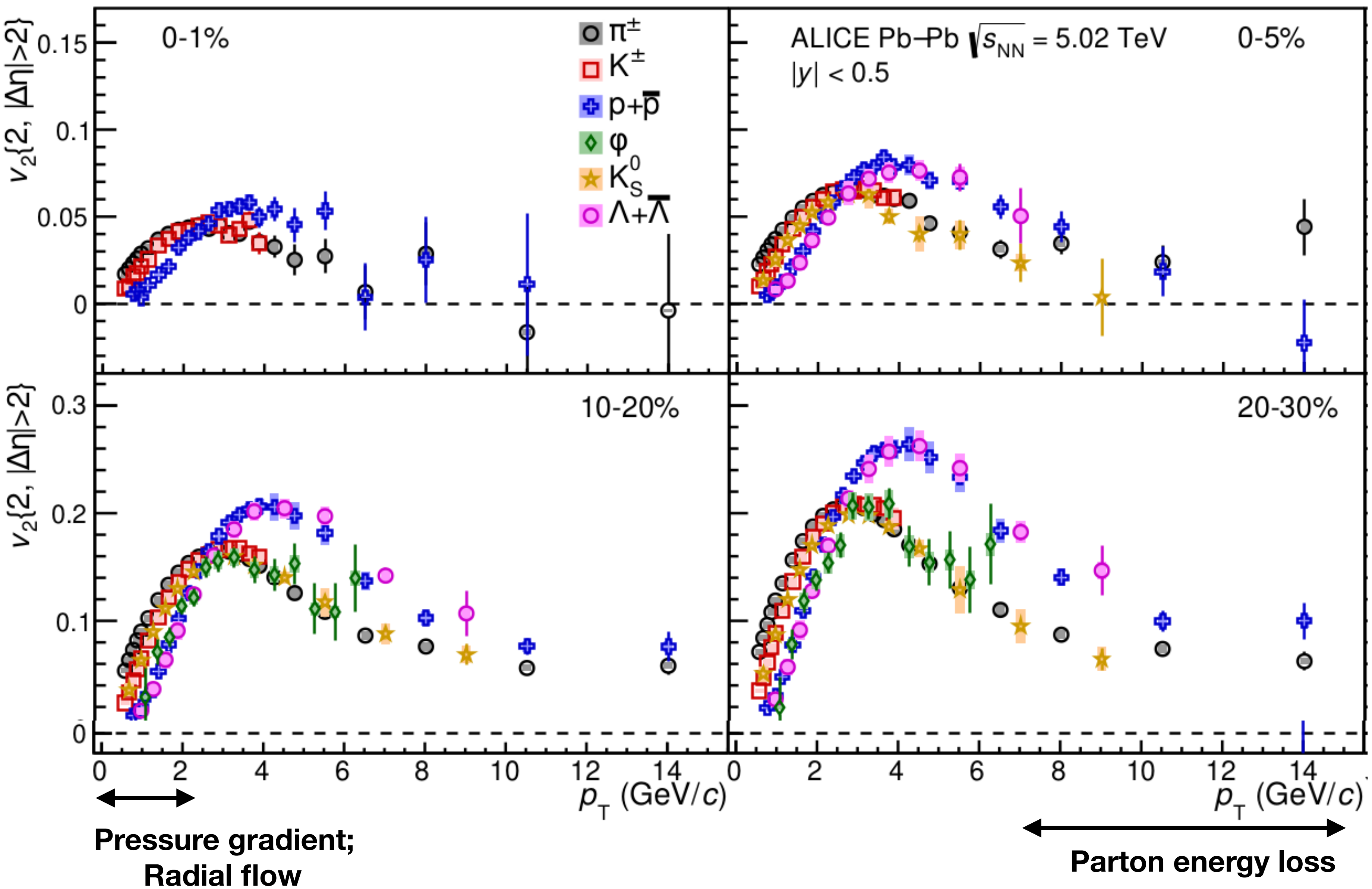
ALICE, PRL 117 (2016) 182301



- Measurements of v_n **consistent with hydrodynamical model calculations**
- Symmetric cumulants (SC) provide further constraints on the initial conditions + transport coefficients
- Together $v_n\{m\}$ + SC(m,n) provide a better handle of the model parameters than each of them independently
- **Origin of collectivity in large collision systems is well understood**.

Slide from R. Bertens et al. (U. Tennessee)

Anisotropic flow of identified particles in Pb–Pb collisions at √sNN = 5.02 TeV



Low-pT (< 2 GeV/c) : Mass ordering (Radial flow) ;
observed at 2.72 TeV, confirmed at 5.02 TeV.
Intermediate-pT (2-7 GeV/c) : Quark number scaling
High-pT (>7 GeV/c): Parton energy loss

ALICE Collaboration, arXiv:1805.04422, Submitted to PRC.

R₂ & P₂ Correlations in Pb - Pb

$$R_2(\Delta\eta,\Delta\phi) \equiv \frac{\rho_2(\Delta\eta,\Delta\phi)}{\rho_1(\eta_1,\phi_1)\otimes\rho_1(\eta_2,\phi_2)} - 1$$

$$P_2(\Delta\eta,\Delta\phi) = \frac{\langle \Delta p_T \Delta p_T \rangle(\Delta\eta,\Delta\phi)}{\langle p_T \rangle^2}$$

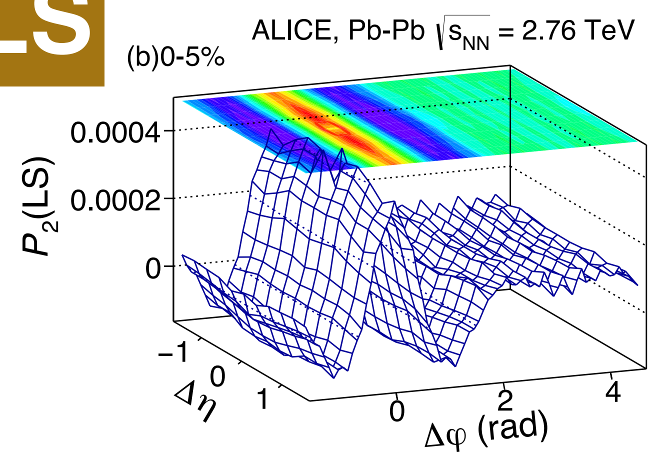
$$\Delta p_T = p_{T,i} - \langle p_T \rangle$$

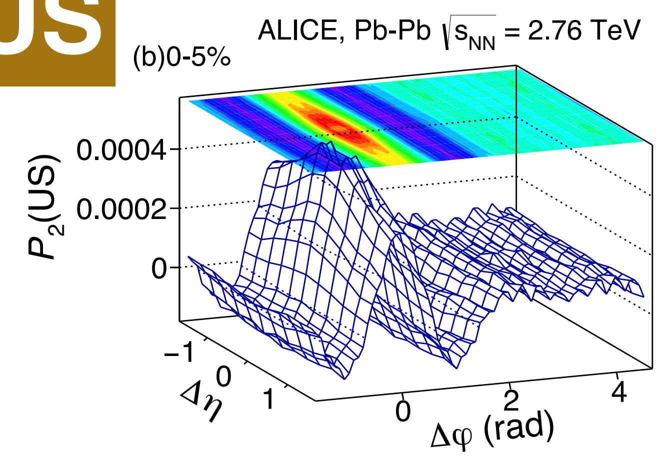
$$\langle \Delta p_T \Delta p_T \rangle(\Delta\eta,\Delta\phi) \equiv \frac{\int \rho_2(\vec{p}_1,\vec{p}_2)\Delta p_{T,1}\Delta p_{T,2}\, dp_{T,1}\, dp_{T,2}}{\rho_2(\Delta\eta,\Delta\phi)}$$

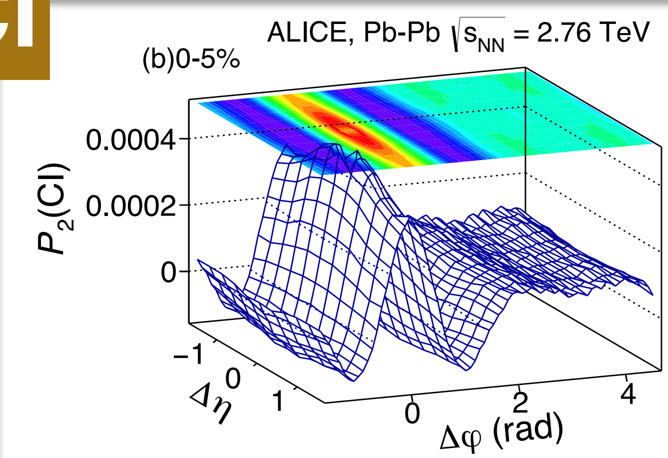
0-5% PbPb Collisions

LS | **US** | **CI**

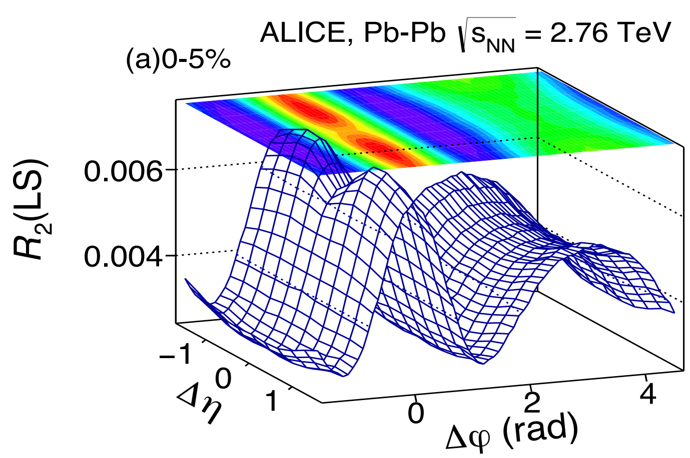
P_2

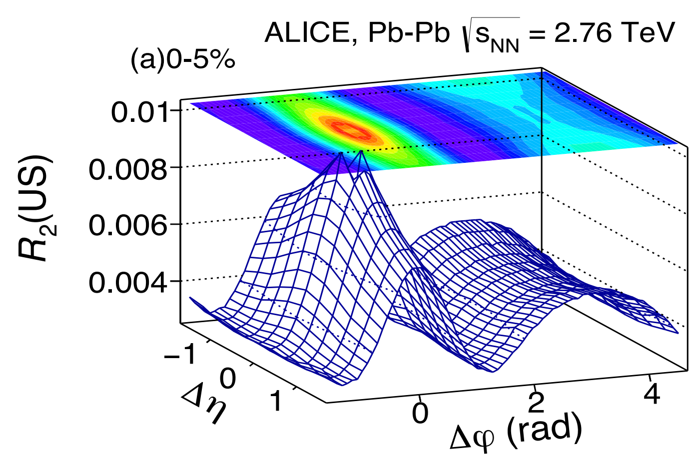


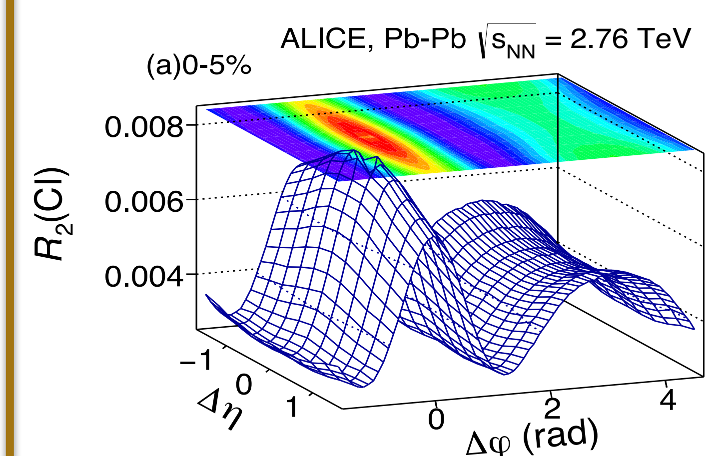




R_2



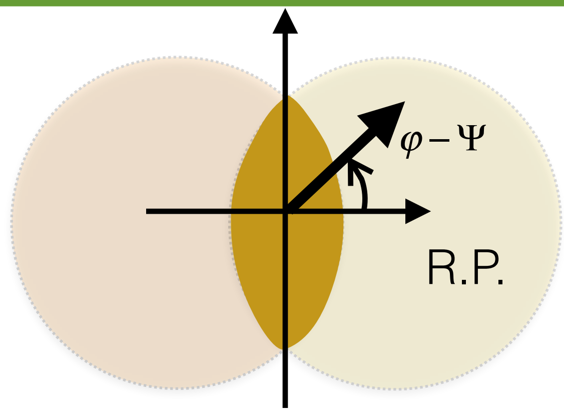




US: Unlike-sign pairs
LS: Like-sign pairs
CI = US + LS

PRL 118 (2017) 162302.

Flow vs. Non-Flow

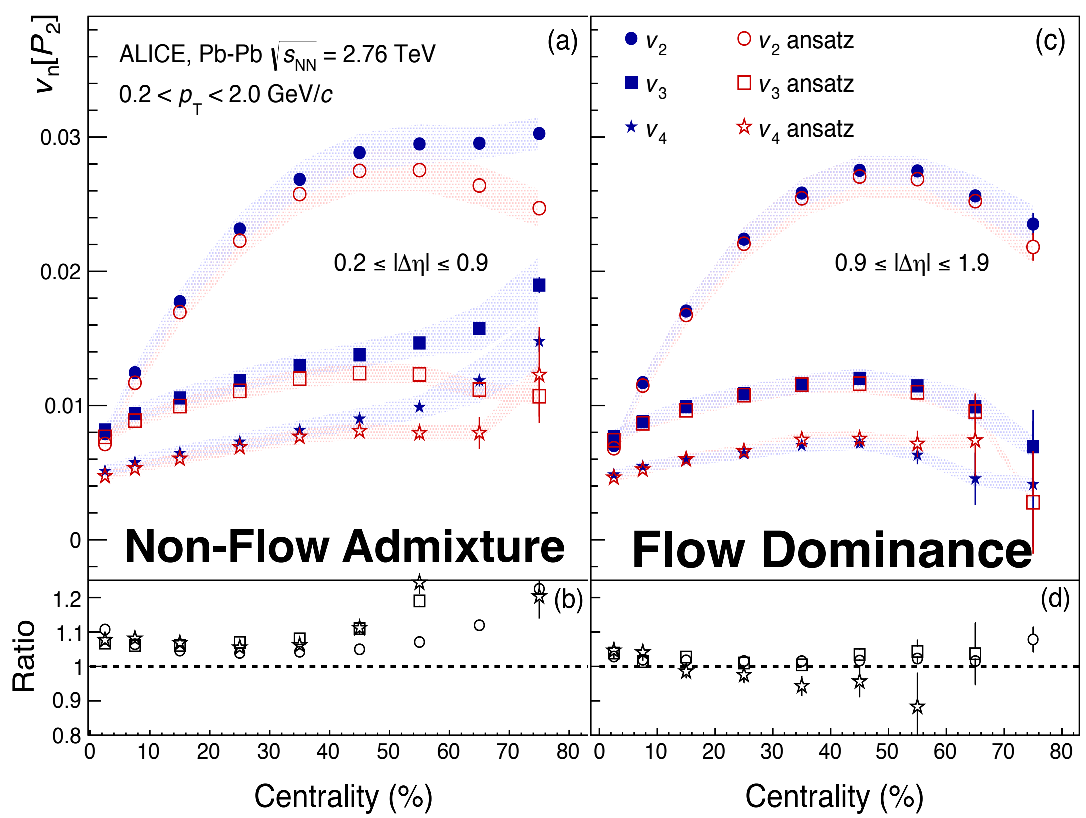


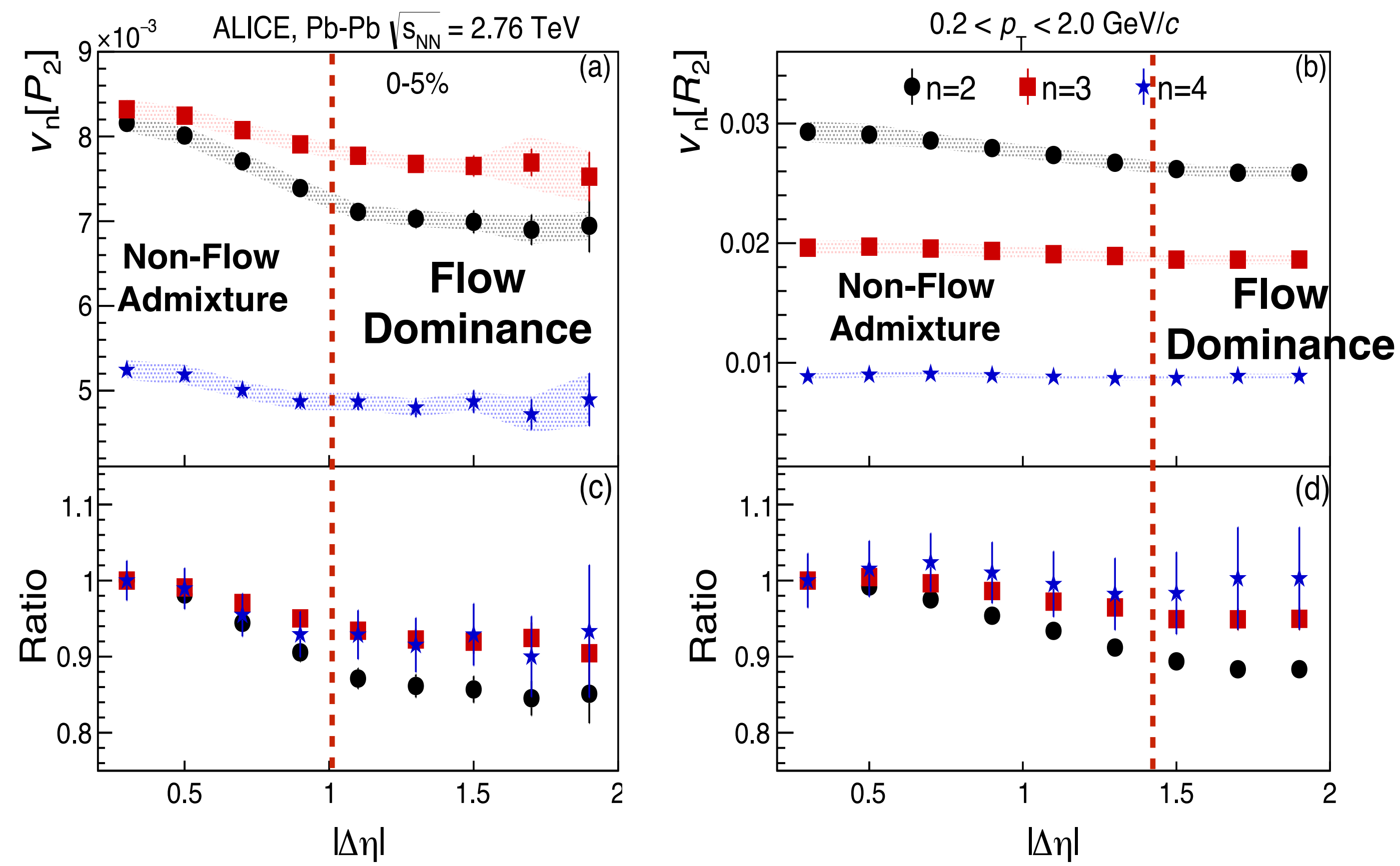
$$v_n[P_2] = \frac{v_n^{pT}}{\langle p_T \rangle} - v_n$$

$$v_n(\eta) = \frac{1}{P_n(\eta)} \int P_n(\eta, p_T) v_n(\eta, p_T) dp_T$$

$$v_n^{p_T}(\eta) = \frac{1}{P_n(\eta)} \int P_n(\eta, p_T) v_n(\eta, p_T) p_T \, dp_T$$

$$\langle p_T \rangle = \frac{1}{P_n(\eta)} \int P_n(\eta, p_T) p_T \, dp_T$$





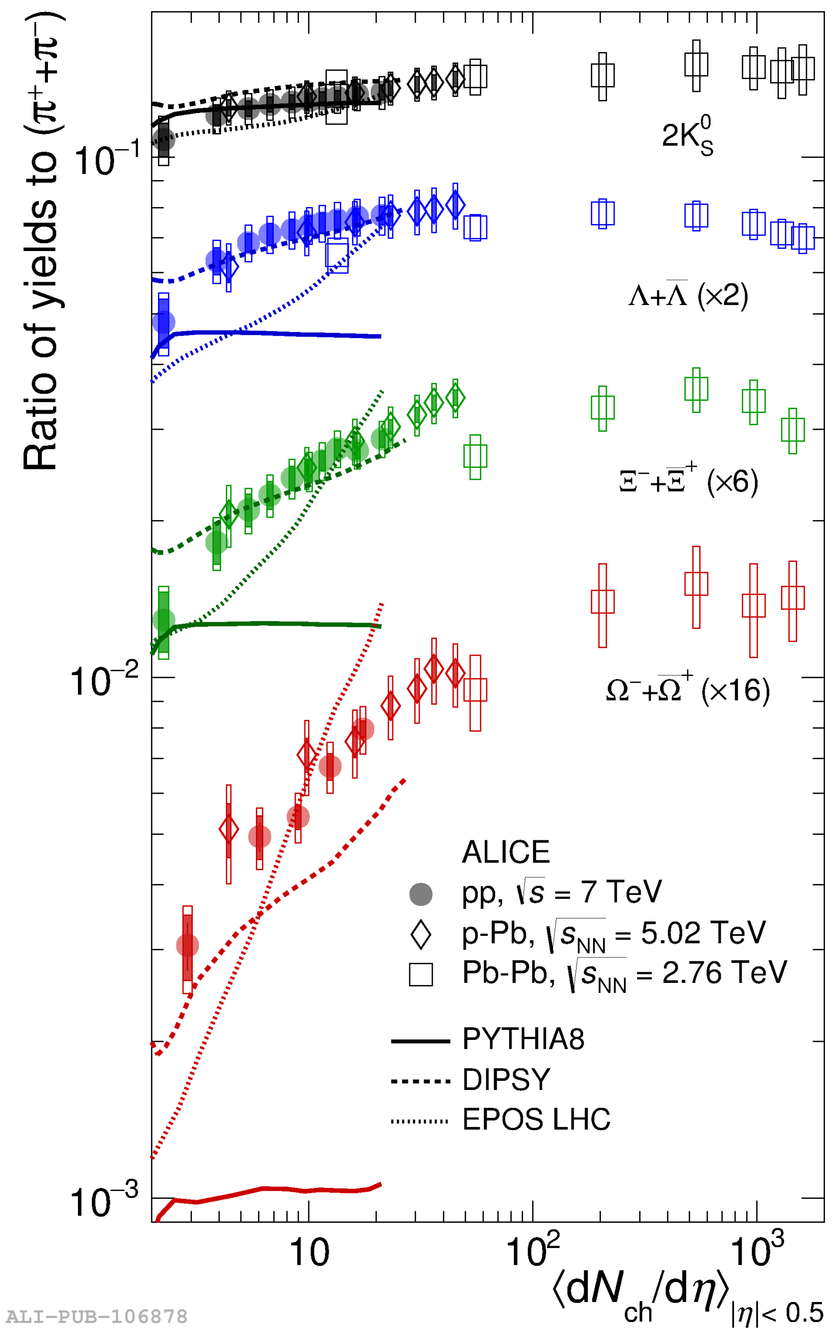
Comparison of correlators P_2 and R_2 indicates collective flow dominance at |Δη|>1 — new evaluation of non-flow effects

Slide from A. Timmins (U Houston)

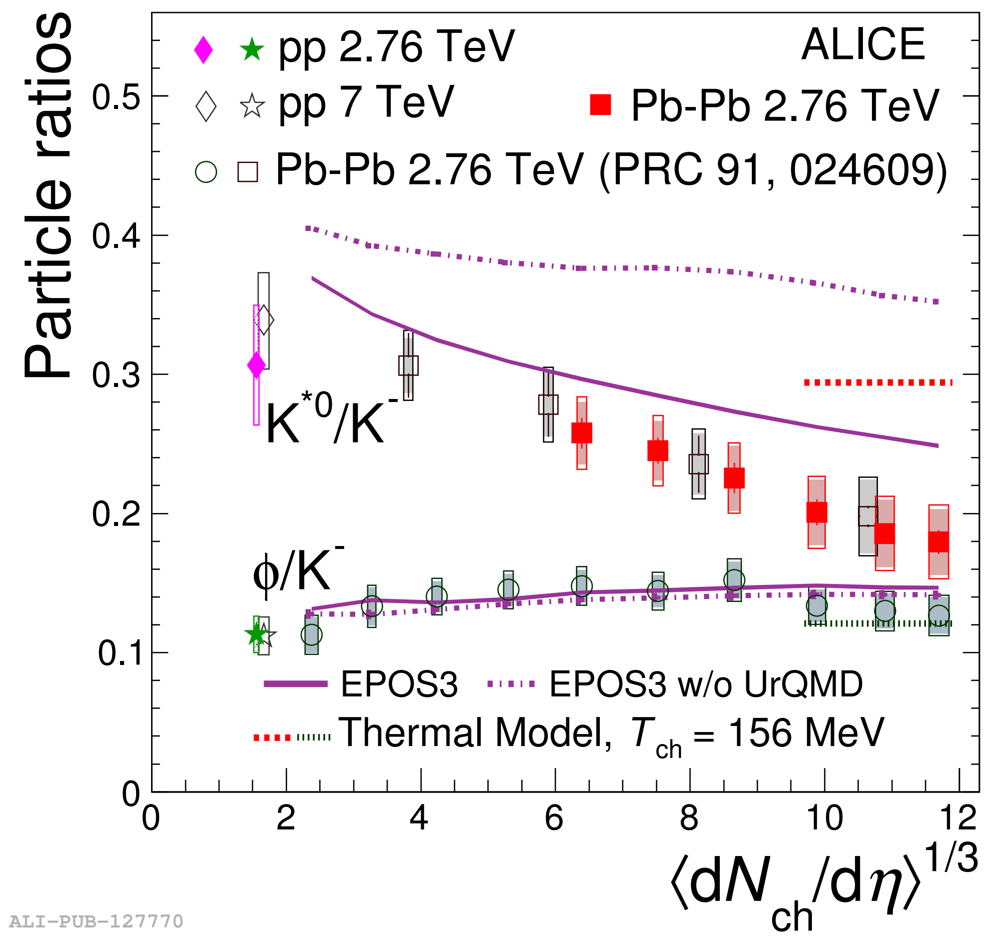
NP 13 (2017) 535–539
PRC 95 (2017) 064606

QGP in small systems?

Enhancement of multi-strange hadrons in pp and p-Pb

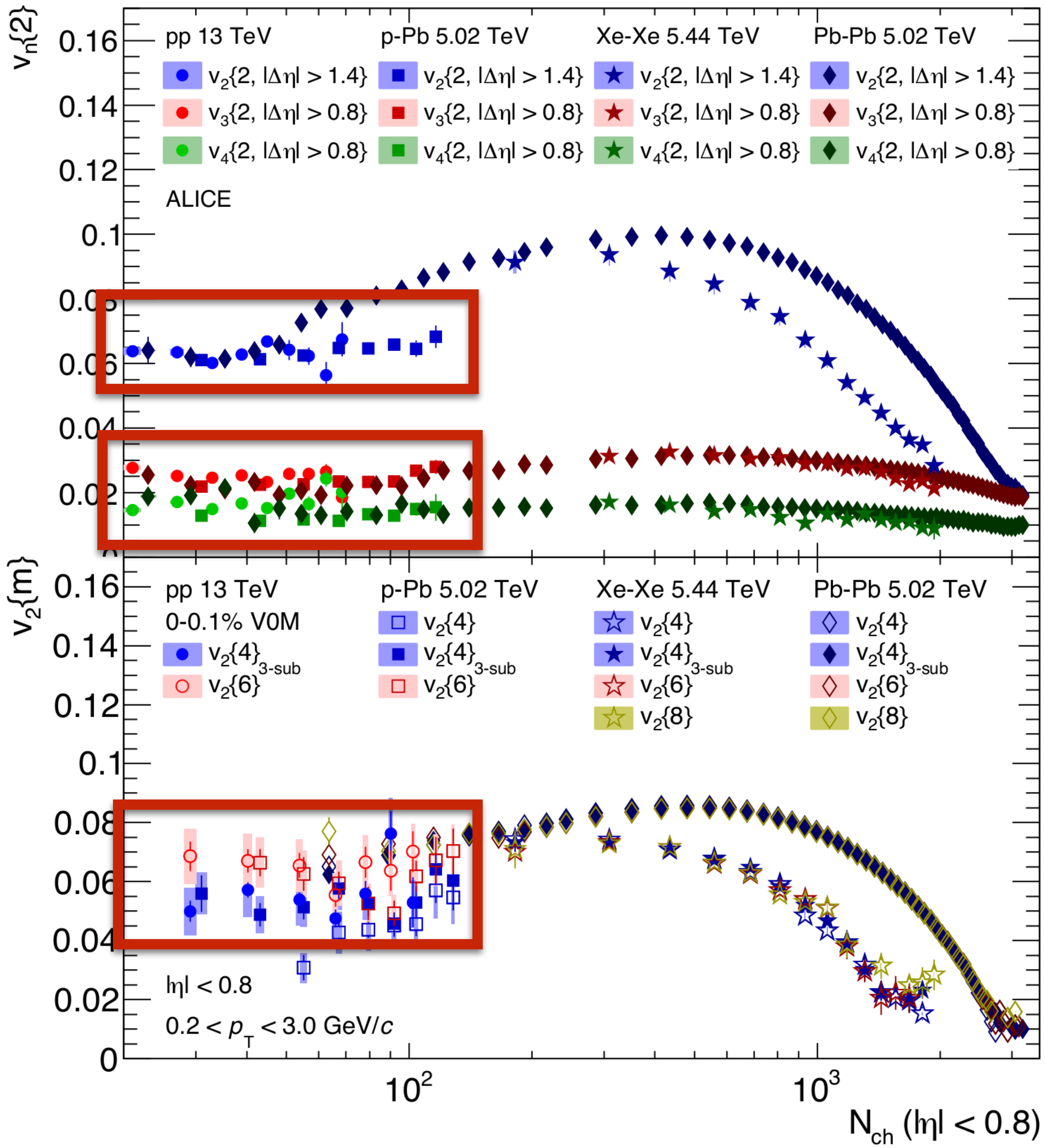


- Do we make a QGP in pp collisions??



- Reduction of K^{*0} relative to K^- in central Pb-Pb consistent with increased re-scattering of decay products in hadronic phase

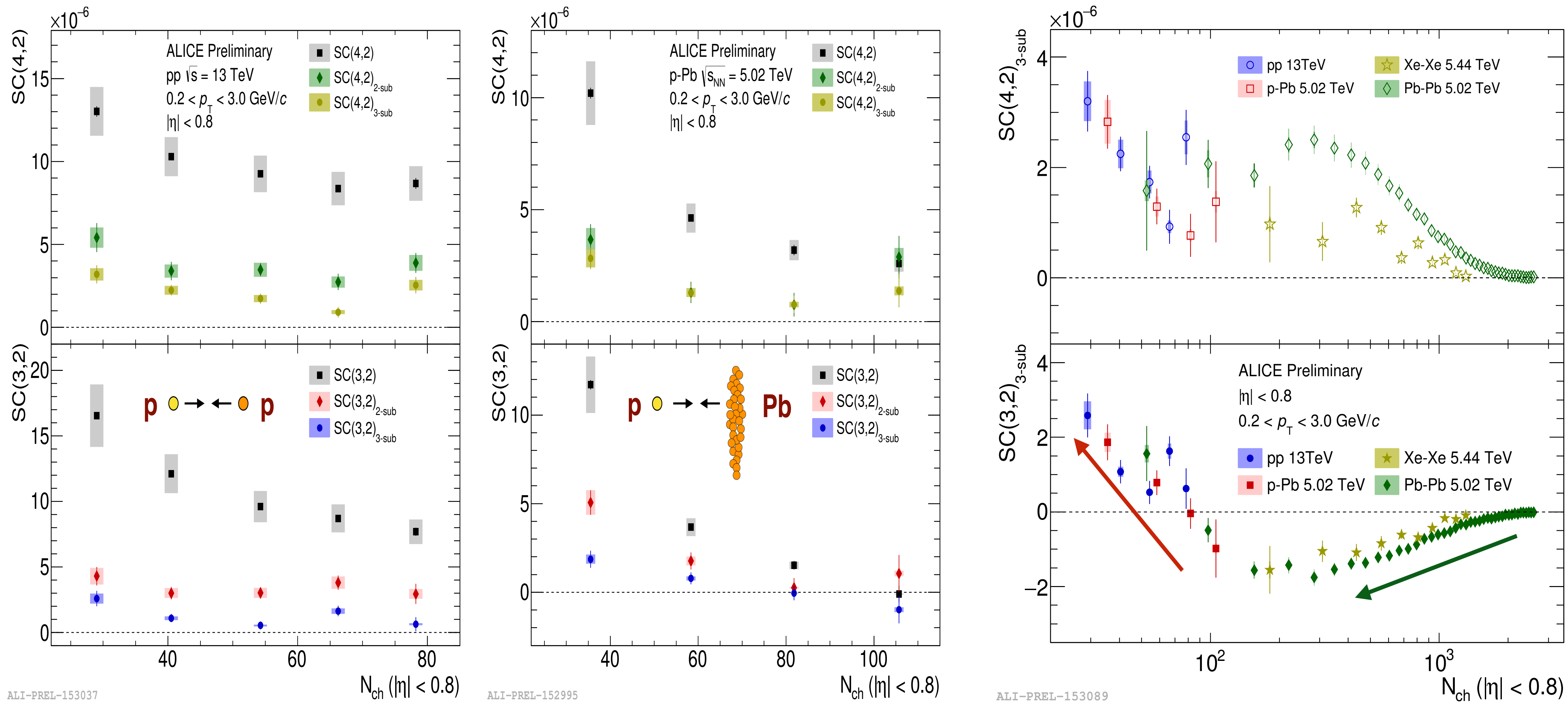
QGP, Collectivity in pp, p–Pb ?



- $v_n\{m\}$ are sensitive to long-range multi-particle correlations.
- $v_n\{m\}$ are large in pp and p-Pb.
  - Indicates presence of long-range multi-particle correlations in this systems
  - What is their origin?
    - Initial state effects,
    - final state effects,
    - both?
- Consider measurements of $SC(m,n)_{3\text{-sub}}$.

SC(m,n): suppression of non-flow effects

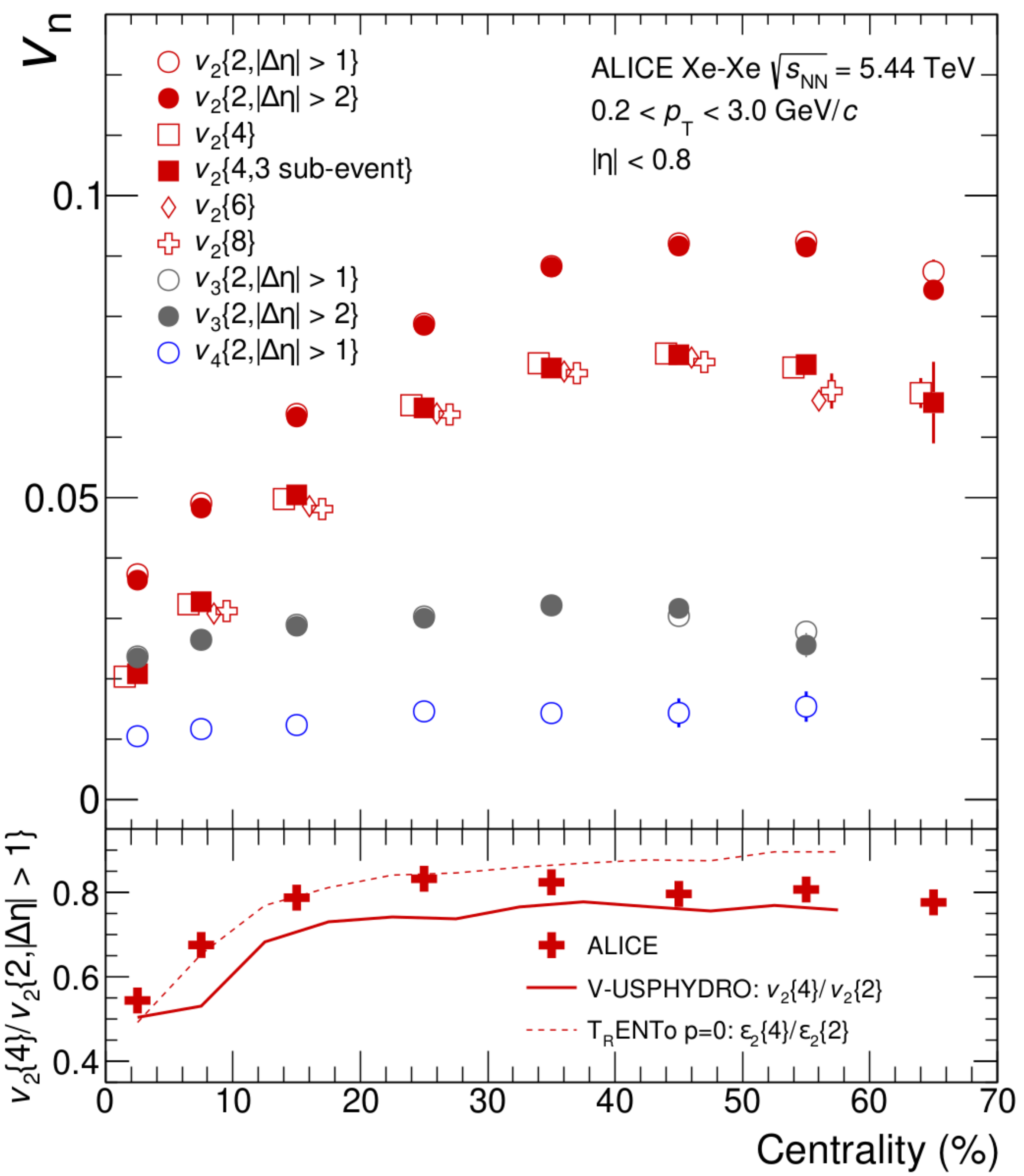
- Need to constrain initial conditions - small systems
- Need better/new measurements - Symmetric Cumulants



- Suppression of non-flow in SC w/ multiple sub-events: SC(m,n) > SC(m,n)$_{2\text{-sub}}$ > SC(m,n)$_{3\text{-sub}}$
- Positive correlation between v_2 and v_4 in all collision systems
- Anti-correlation between v_2 and v_3 at large multiplicities — initial eccentricity correlations
- A transition to positive correlations followed by both small and large systems
- **Not described by non-flow only models, but qualitatively by models with initial state**

PLB 784 (2018) 82-95

Flow coefficients in Xe — Xe Collisions

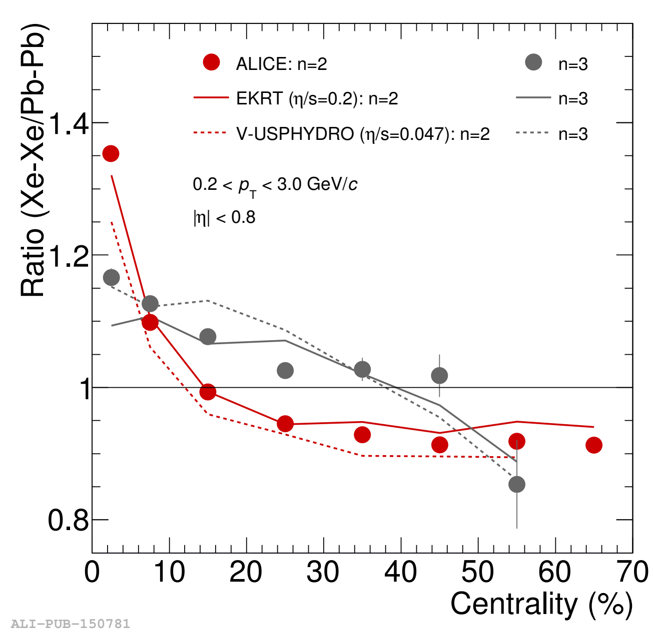


- **First measurements** of v_2, v_3, v_4 in Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV
- $v_2\{4\}/v_2\{2\}$ sensitive to **flow fluctuations**: qualitatively described by initial conditions, some tension with hydro model predictions[1]
- Models include **nuclear deformation** β_2, which modifies Wood-Saxon as

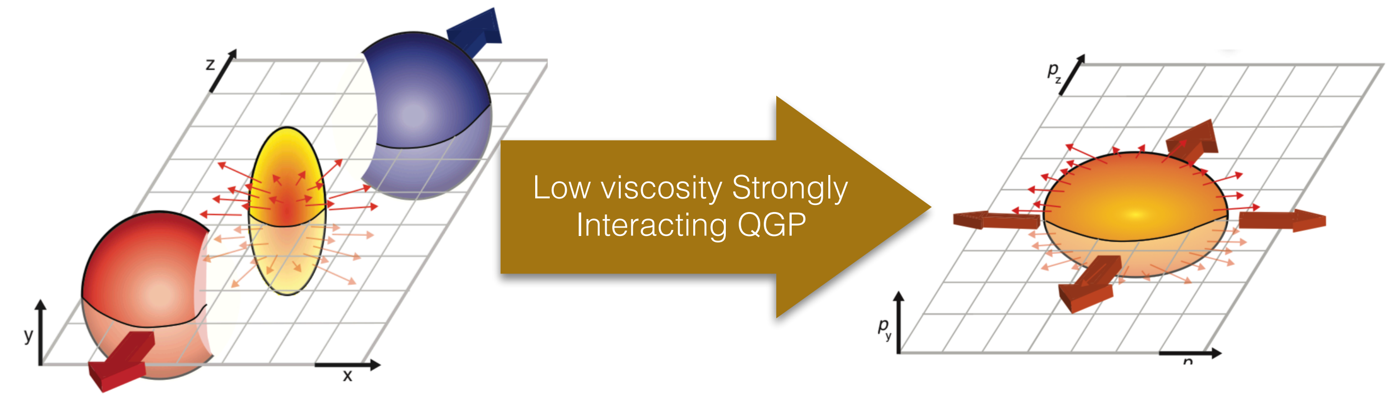
$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r - R_0 - R_0\, \beta_2\, Y_{20}(\theta))/a}}$$

ρ_0 density at center, R_0 nuclear radius, r distance from center, Y_{20} Bessel function of secon kind, a skin depth

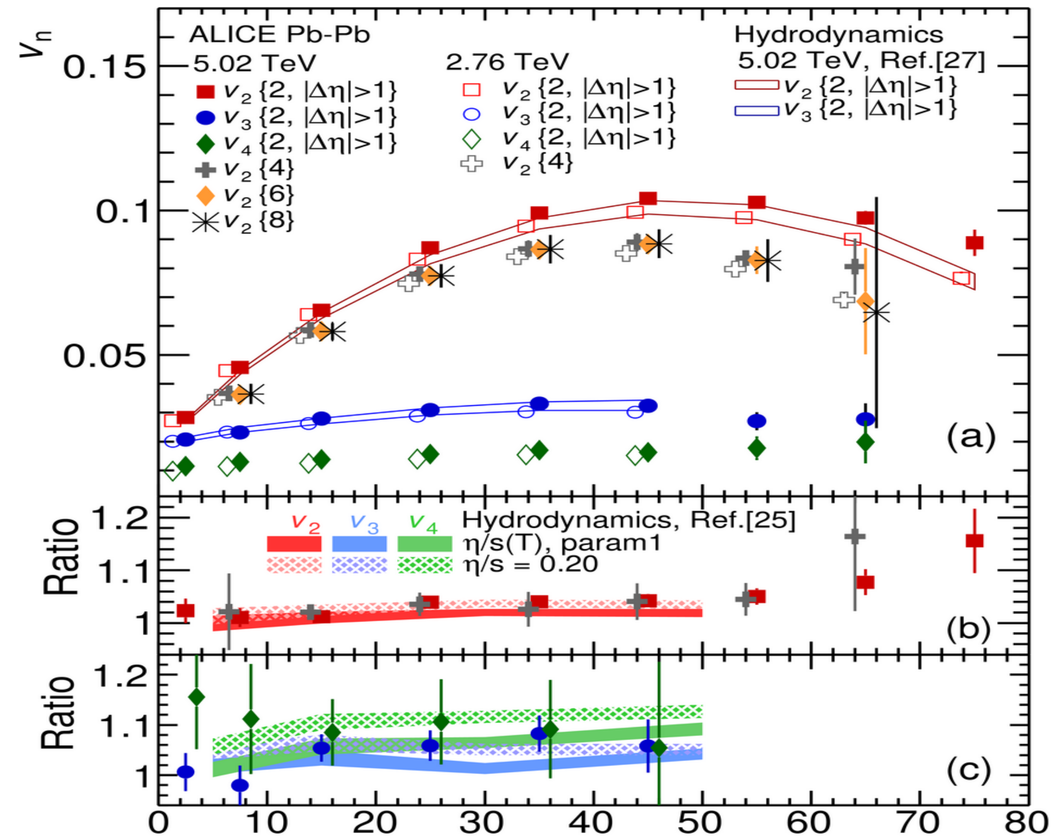
Effect: $\sim 20\%$ larger $v_2\{2\}$ in central, decreasing towards peripheral



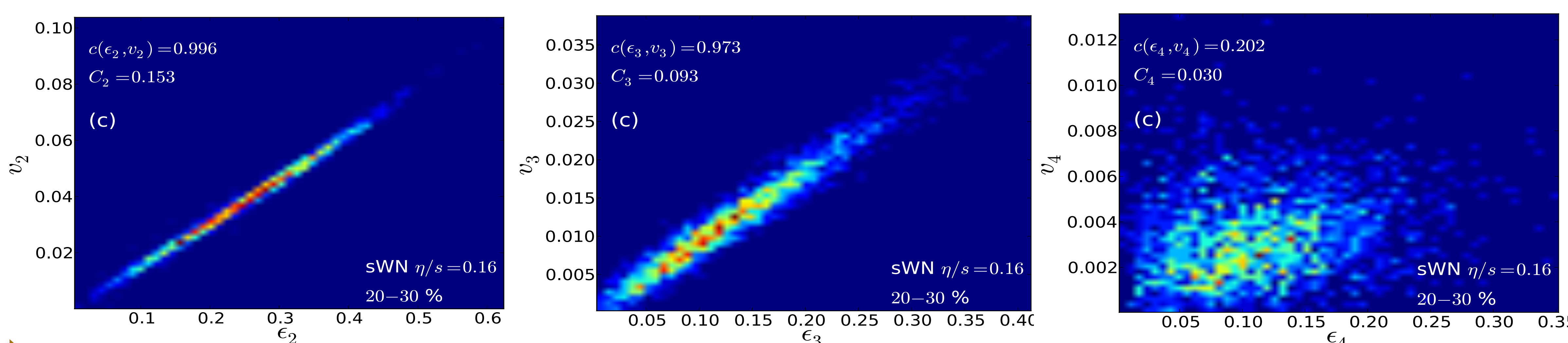
Measuring/Constraining QGP properties



- Flow harmonics constrain initial conditions and transport properties: η/s, ζ/s, EoS, freeze-out conditions.
- Higher harmonics probe smaller spatial scales
  - More sensitive to transport properties (e.g. η/s) and initial density profile
- Testing details of hydrodynamical response of QGP



Phys. Rev. Lett. 116 (2016) 132302



HI

Phys. Rev. C 87, 054901
H. Niemi *et al*.

$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} \quad (n > 3)$$

Linear vs. Non-linear response of higher harmonics

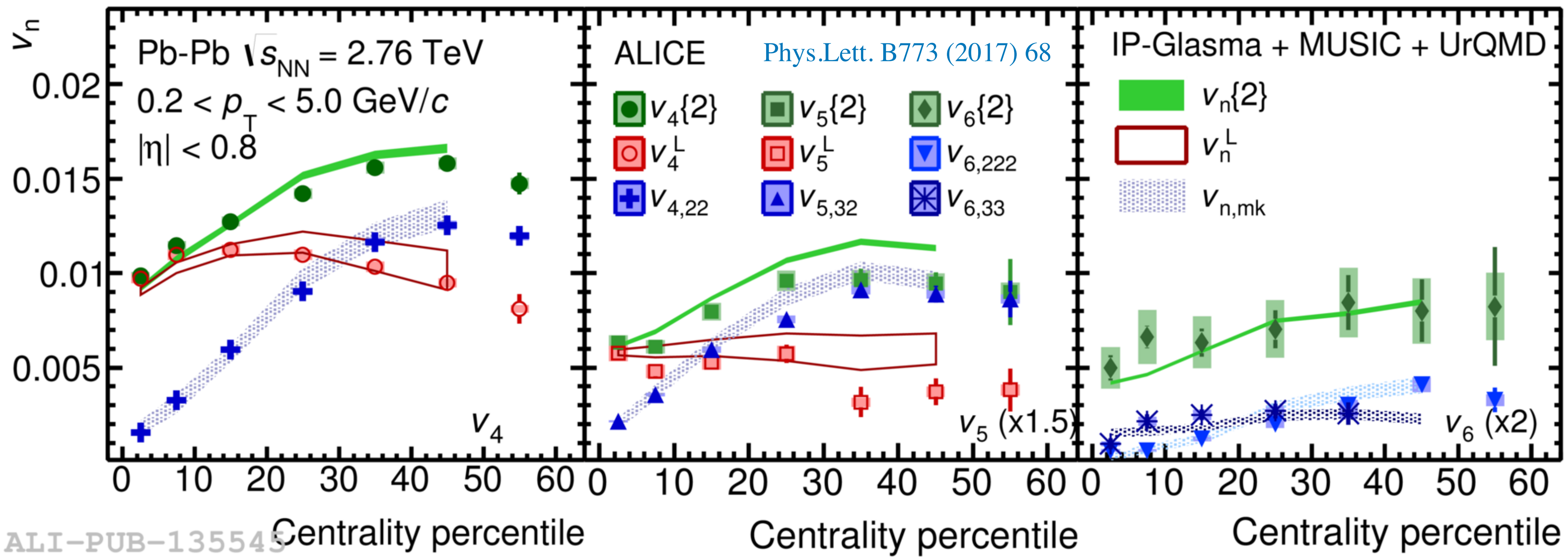
- **V_n^{L} proportional to spatial anisotropy ε_n** (same order)
- **V_n^{NL} proportional to lower order spatial anisotropies**, e.g. ε_2 and/or ε_3 when n>3
- V_n^{L} and V_n^{NL} statistically uncorrelated

$$V_4 = V_4^{\mathrm{NL}} + V_4^{\mathrm{L}} = \chi_{4,22}(V_2)^2 + V_4^{\mathrm{L}}$$

$$V_5 = V_5^{\mathrm{NL}} + V_5^{\mathrm{L}} = \chi_{5,32}V_3V_2 + V_5^{\mathrm{L}}$$

$$V_6 = V_6^{\mathrm{NL}} + V_6^{\mathrm{L}} = \chi_{6,222}(V_2)^3 + \chi_{6,33}(V_3)^2 + \chi_{6,24}V_2V_4^{\mathrm{L}} + V_6^{\mathrm{L}}$$

Phys. Lett. B773 (2017) 68



$$v_{4,22} = \frac{\langle v_4 v_2^2 \, cos(4\Psi_4 - 4\Psi_2)\rangle}{\sqrt{\langle v_2^4\rangle}}$$

$$v_{5,32} = \frac{\langle v_5 v_3 v_2 \, cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle}{\sqrt{\langle v_3^2 v_2^2\rangle}}$$

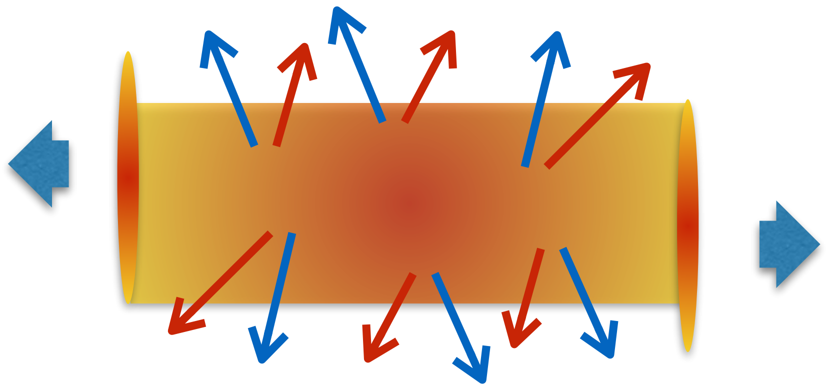
$$v_{6,33} = \frac{\langle v_6 v_3^2 \, cos(6\Psi_6 - 6\Psi_3)\rangle}{\sqrt{\langle v_3^4\rangle}}$$

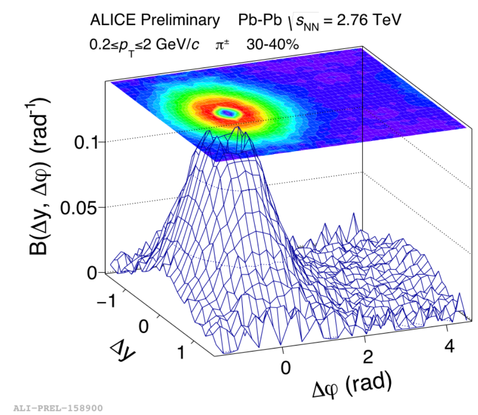
- Non-linear modes are more sensitive to initial state fluctuations + transport properties (η/s, ζ/s)[1]
- For different particle species, additionally probe[2]
  - Effects of hadronisation mechanism, e.g. quark coalescence
  - Effects of hadronic rescattering

(1) Phys.Lett. B773 (2017) 68
(2) JHEP 1609 (2016) 164

Balance Functions

Bass, Danielewicz, Pratt PRL. 85, 2689 (2000)
Pratt, Cheng PRC 68, 014907 (2003)
Bozek PLB 609 (2005) 247–251
Pratt PRL. 108, 212301 (2012)
Kapusta, Plumberg PRC 97, 014906 (2018)

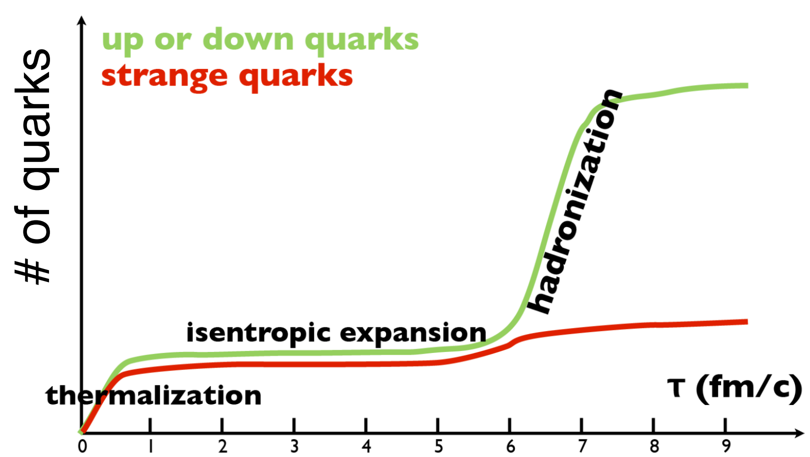


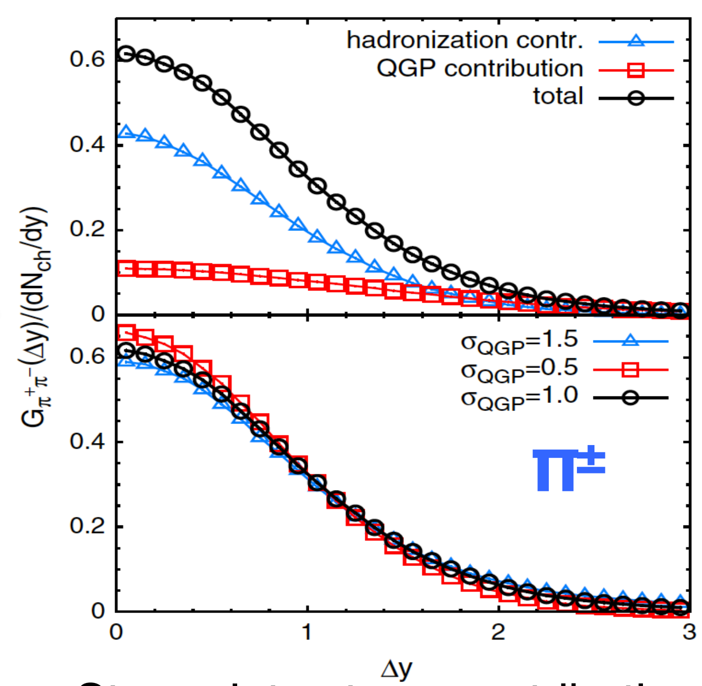


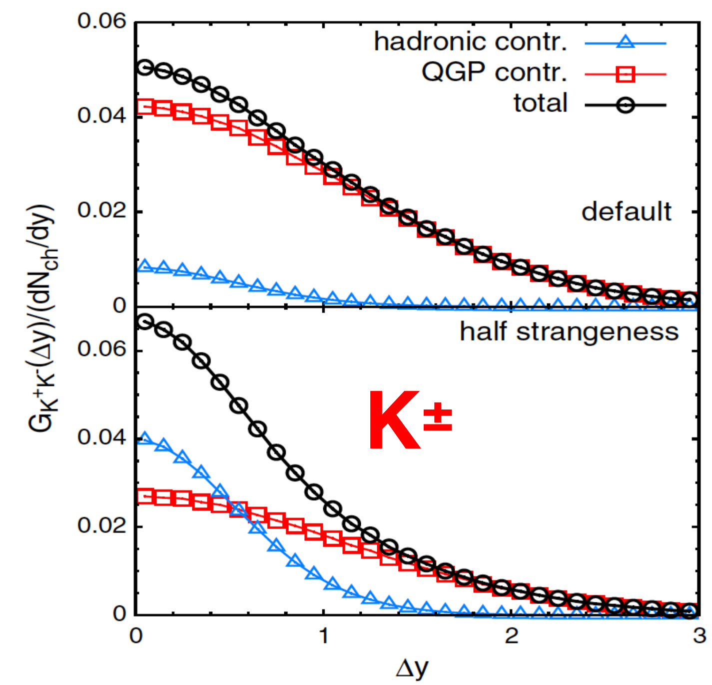
$$B(\Delta y, \Delta\phi) = \frac{dN}{d\eta} R_2^{CD}(\Delta y, \Delta\phi)$$

Correlations: Coordinate Space ⟶ **Correlations:Momentum Space**

Quark Production vs. Time







Two-wave quark production model:
- **π±** : predominantly produced at late stage
- **K±** : predominantly produced at early stage

- Strong late stage contribution
- Hadronization part narrower
- Narrows with centrality

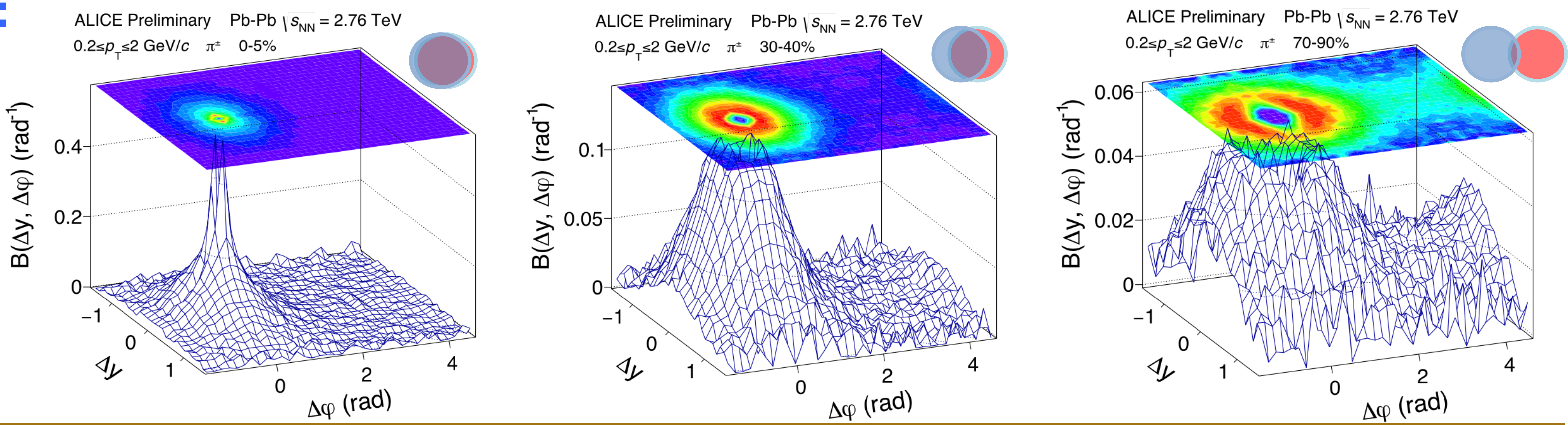
- Weak late stage contribution
- Weak centrality dependence.

Investigate if BFs for **π±**, **K±, …,** evolve differently with centrality at LHC & RHIC (BES)

A tool for studying the chemical evolution of the quark-gluon plasma

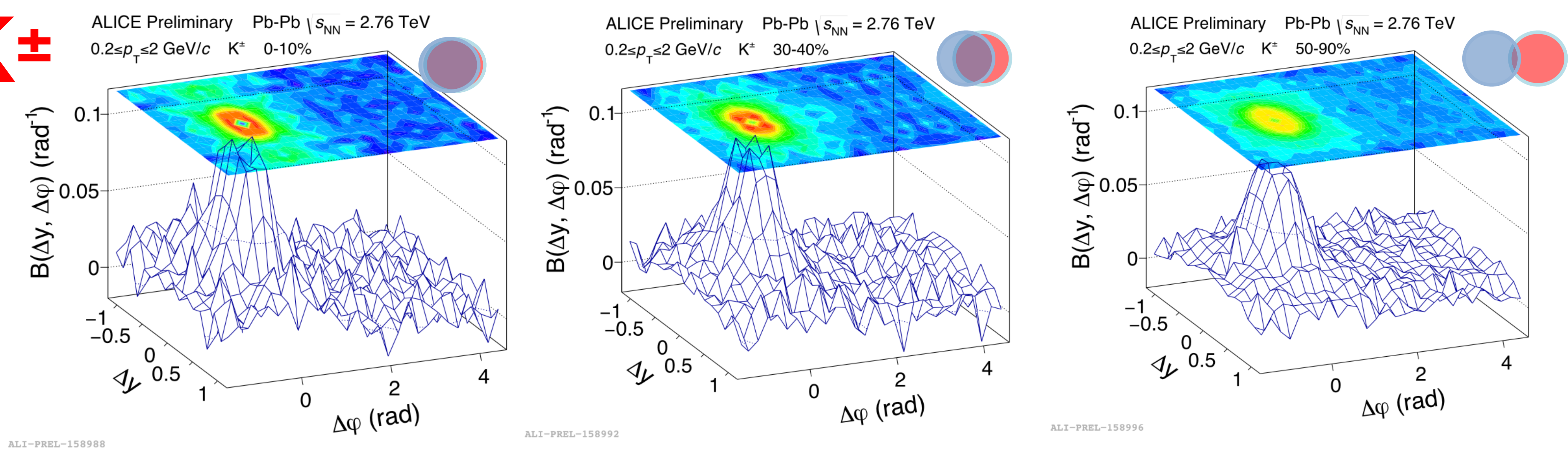
Pion, Kaon Balance Functions

π±



π± : Considerable shape dependence on collision centrality

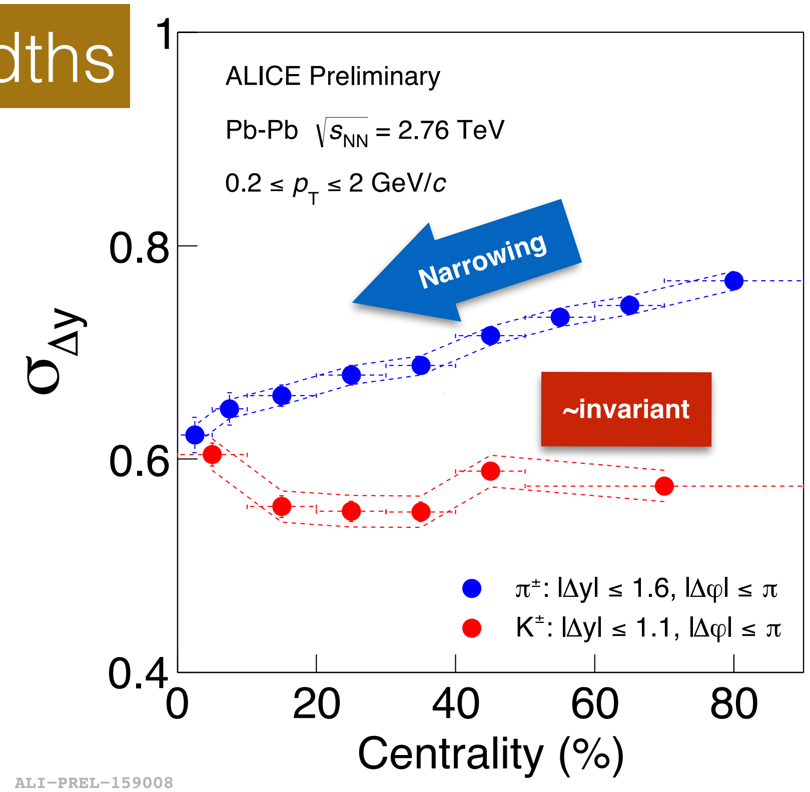
K±

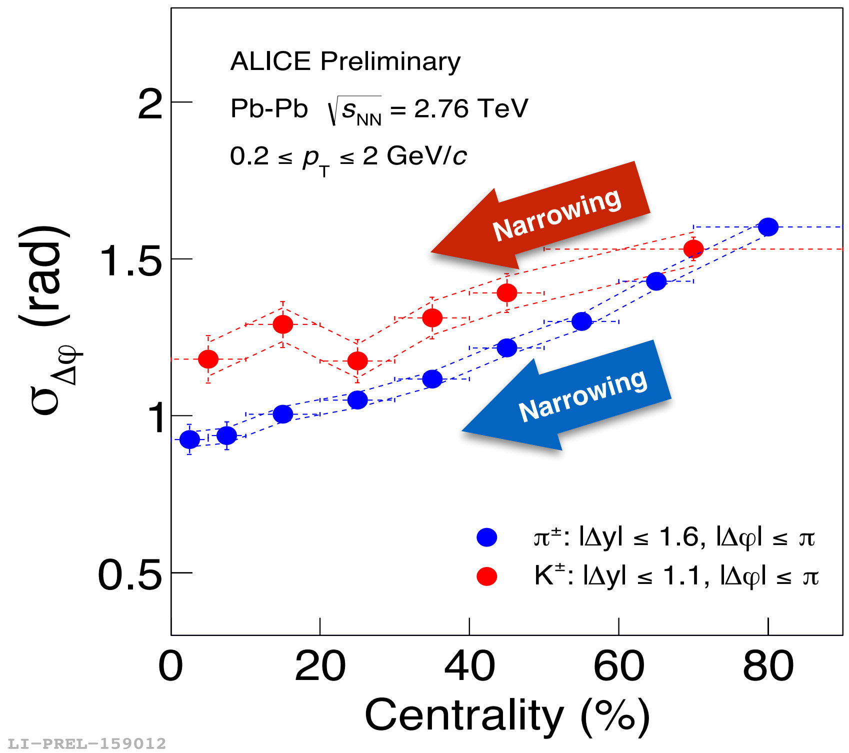


K± : Modest shape dependence on collision centrality

Hadron, Pion, Kaon Balance Functions — Pb-Pb

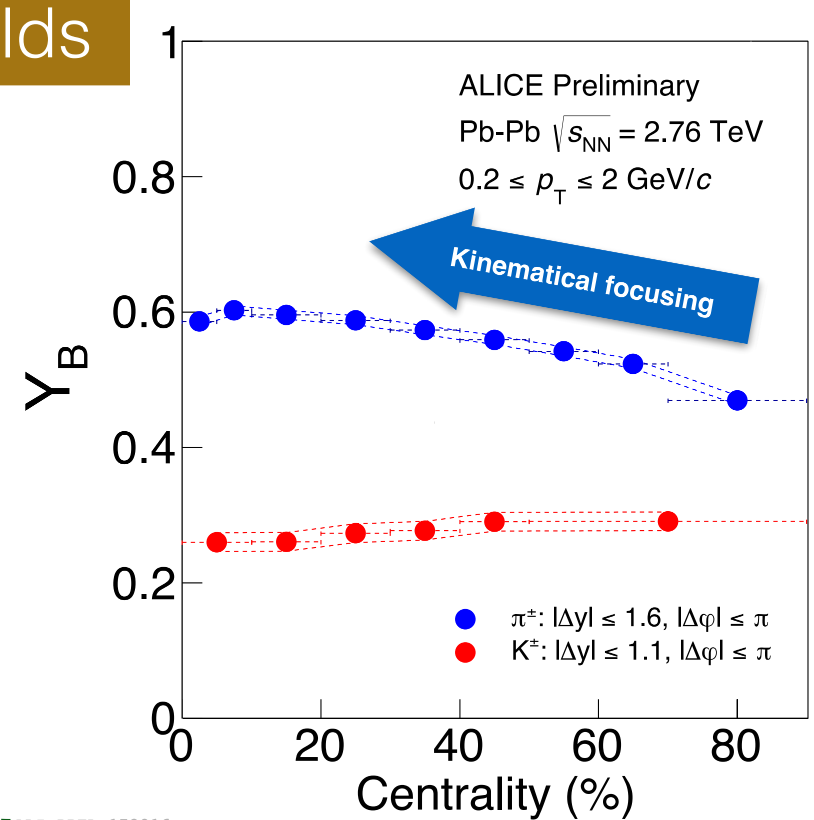
BF Widths

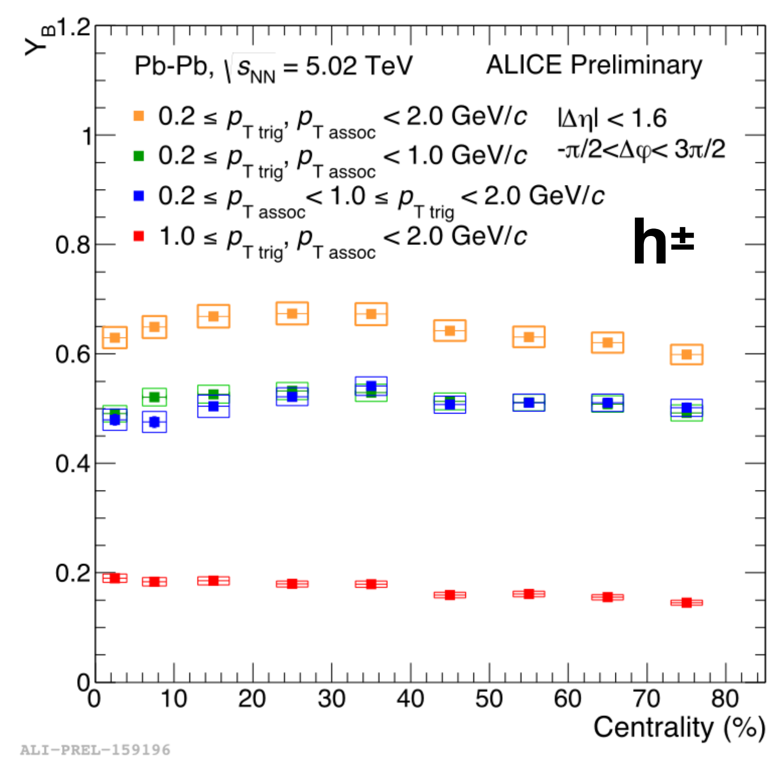




- Large radial flow in PbPb
- Delayed hadronization(?!)

BF Yields



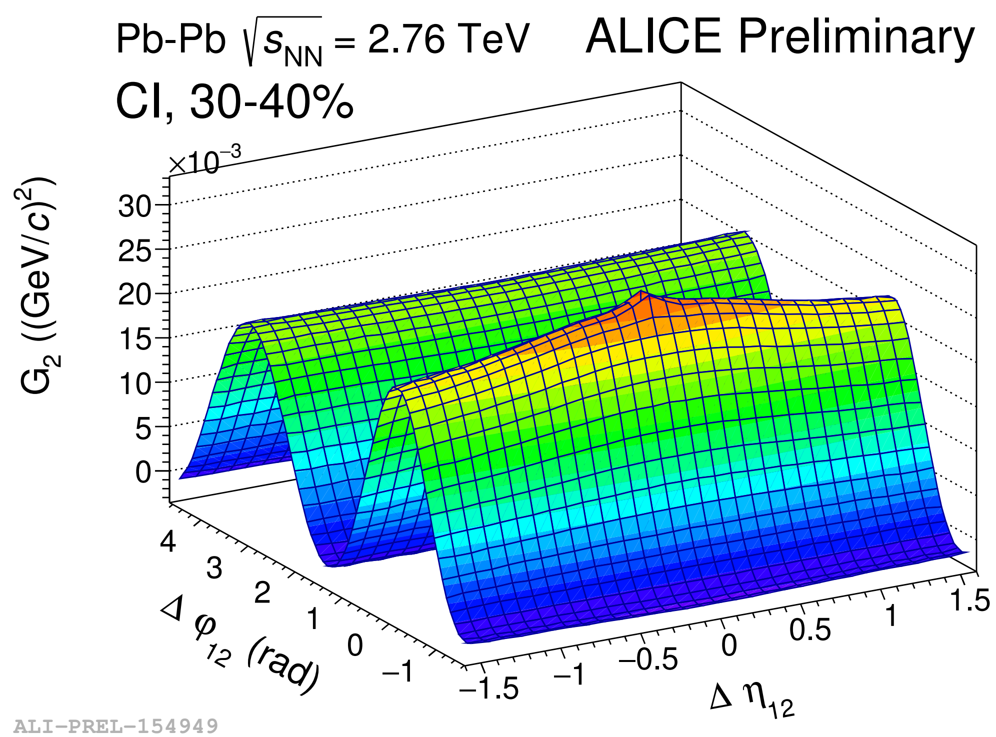


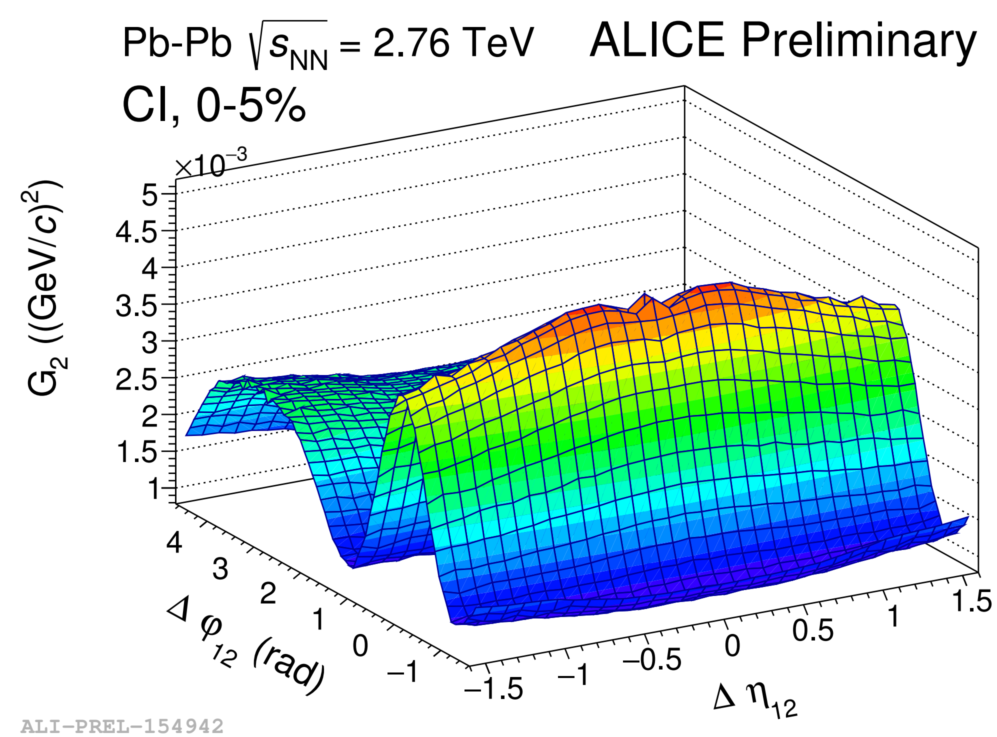
- Constraints on
  - QGP expansion dynamics
  - Hadro-chemistry of the QGP

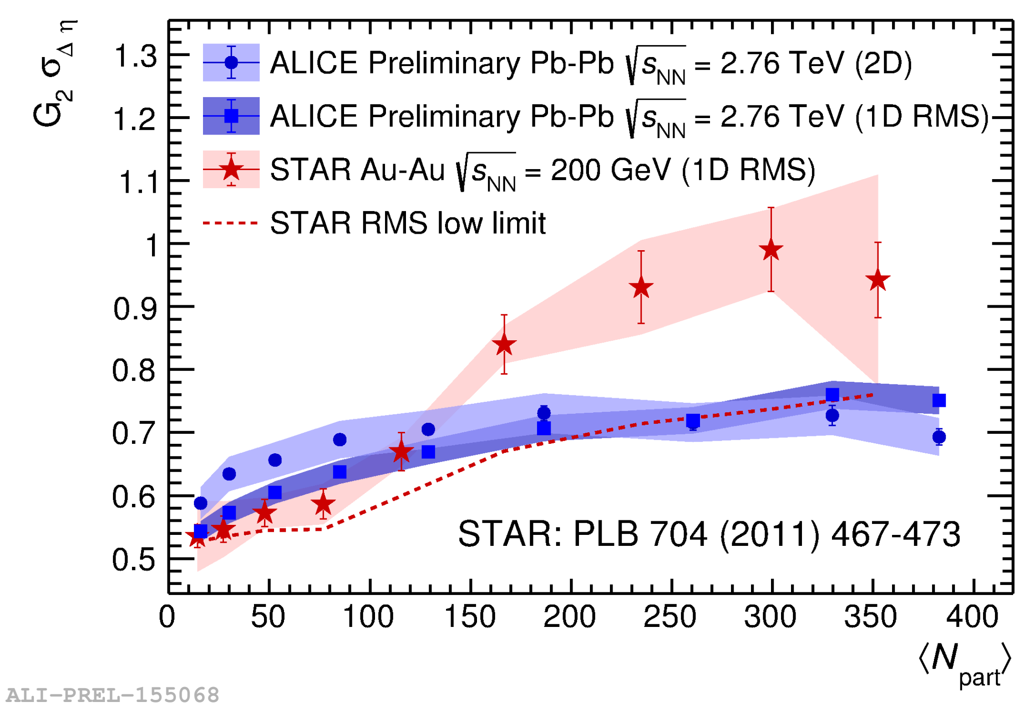
Momentum Correlator G_2

$$G_2(\Delta\eta,\Delta\phi) \equiv \frac{\int \rho_2(\vec{p}_1,\vec{p}_2)\, p_{T,1}\, p_{T,2}\, dp_{T,1}\, dp_{T,2}}{\rho_1(\eta_1,\phi_1) \otimes \rho_1(\eta_2,\phi_2)} - \langle p_{T,1}\rangle\langle p_{T,2}\rangle$$

S. Gavin Phys.Rev.Lett. 97 (2006) 162302
M. Sharma & C.P. et al (STAR), PLB704, 467 (2011)



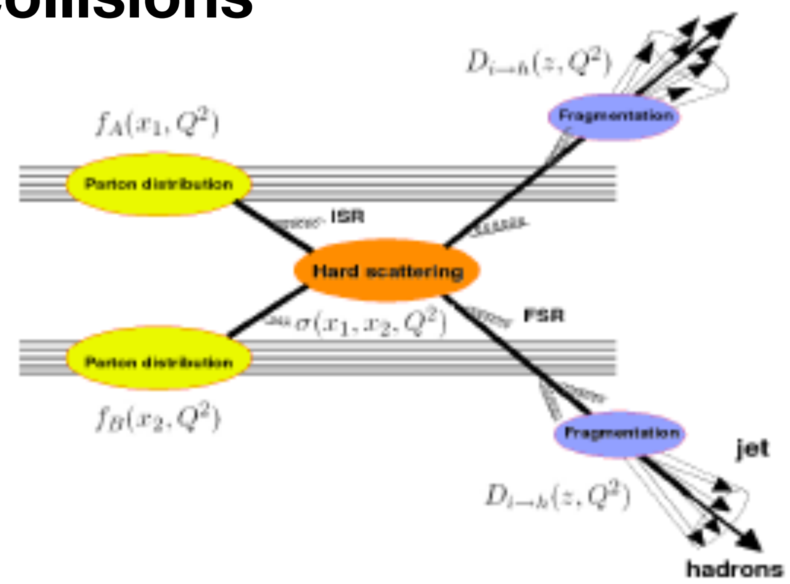




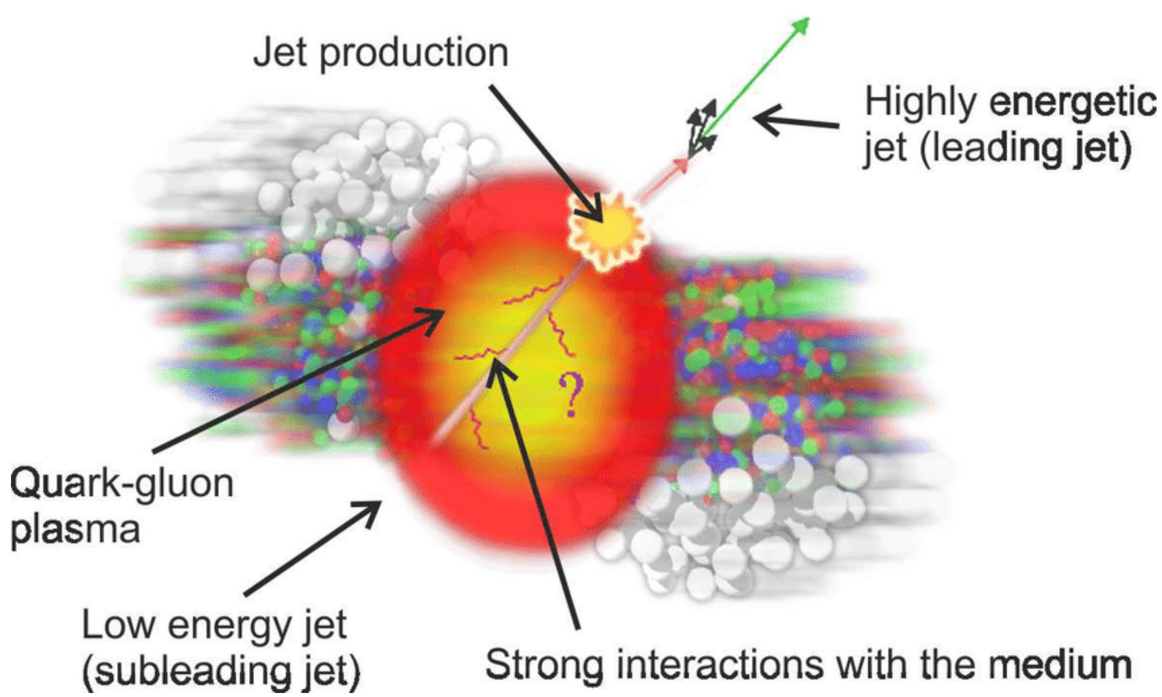
- Broadening of G2 w/ centrality
- Less broadening at LHC
- In progress: using longitudinal broadening to estimate the shear viscosity viscosity at LHC ?

Jet - Medium Interactions

p+p collisions



A+A collisions



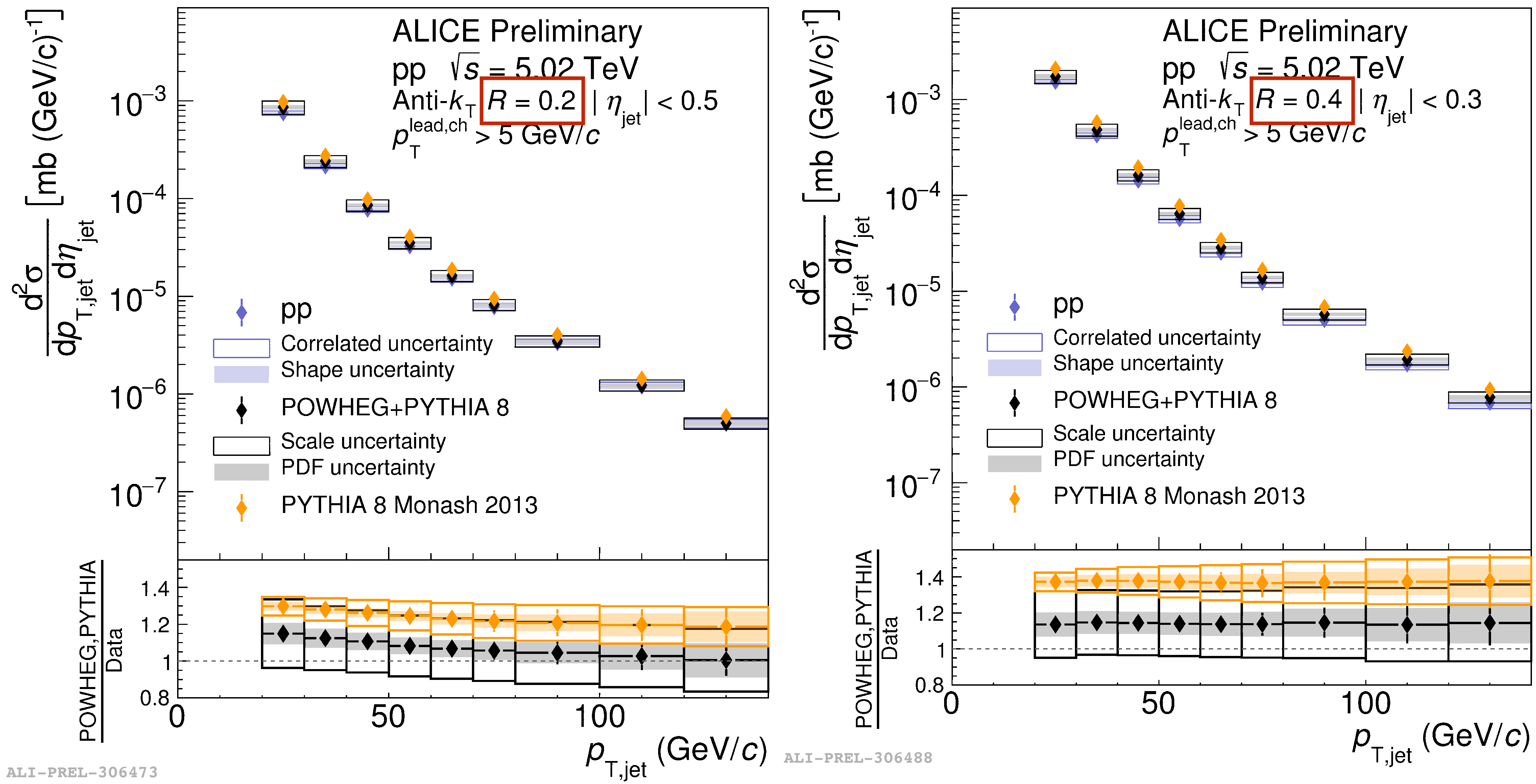
- Use jets from p+p collisions as "calibration"
- Use jets in A+A collisions as self-generated probes to study the properties of the matter produced.
- Initially, such studies were conducted w/ leading particles.
- Today, studies are carried out with charged jets, full jets, and even heavy-flavor jets.

- Topics of interest
  - Jet suppression (energy-loss)
  - Jet modification by medium
  - Medium modification (recoil) by jet.

Slides from James Mulligan, Yale University; Hard Probes 2018

Jet cross-section in p + p collisions @ 5.02 TeV

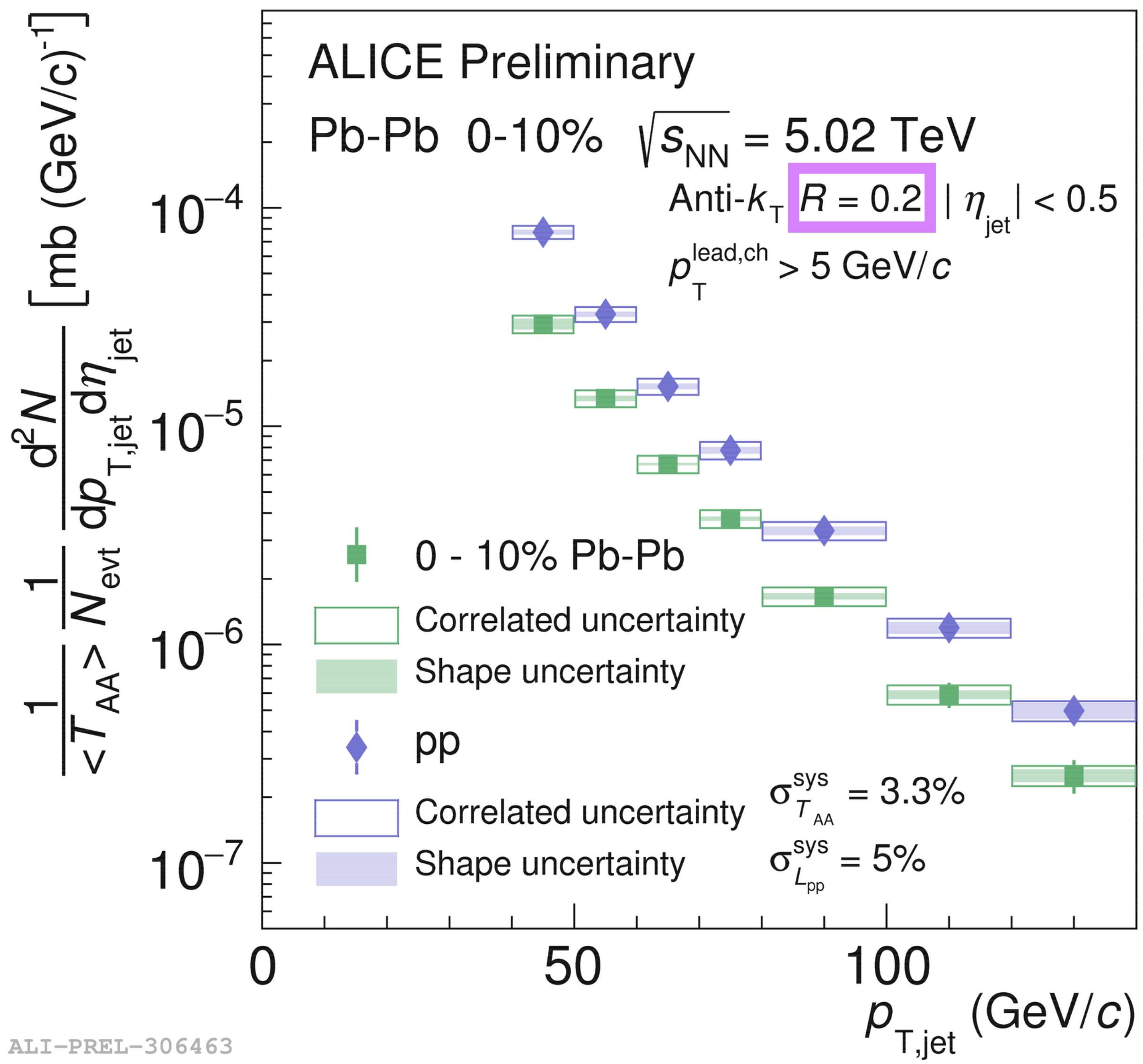
$40 < p_{T,Jet} < 140$ GeV/c Jet reconstruction w/ Anti-k_T; cone sizes: 0.2, 0.4

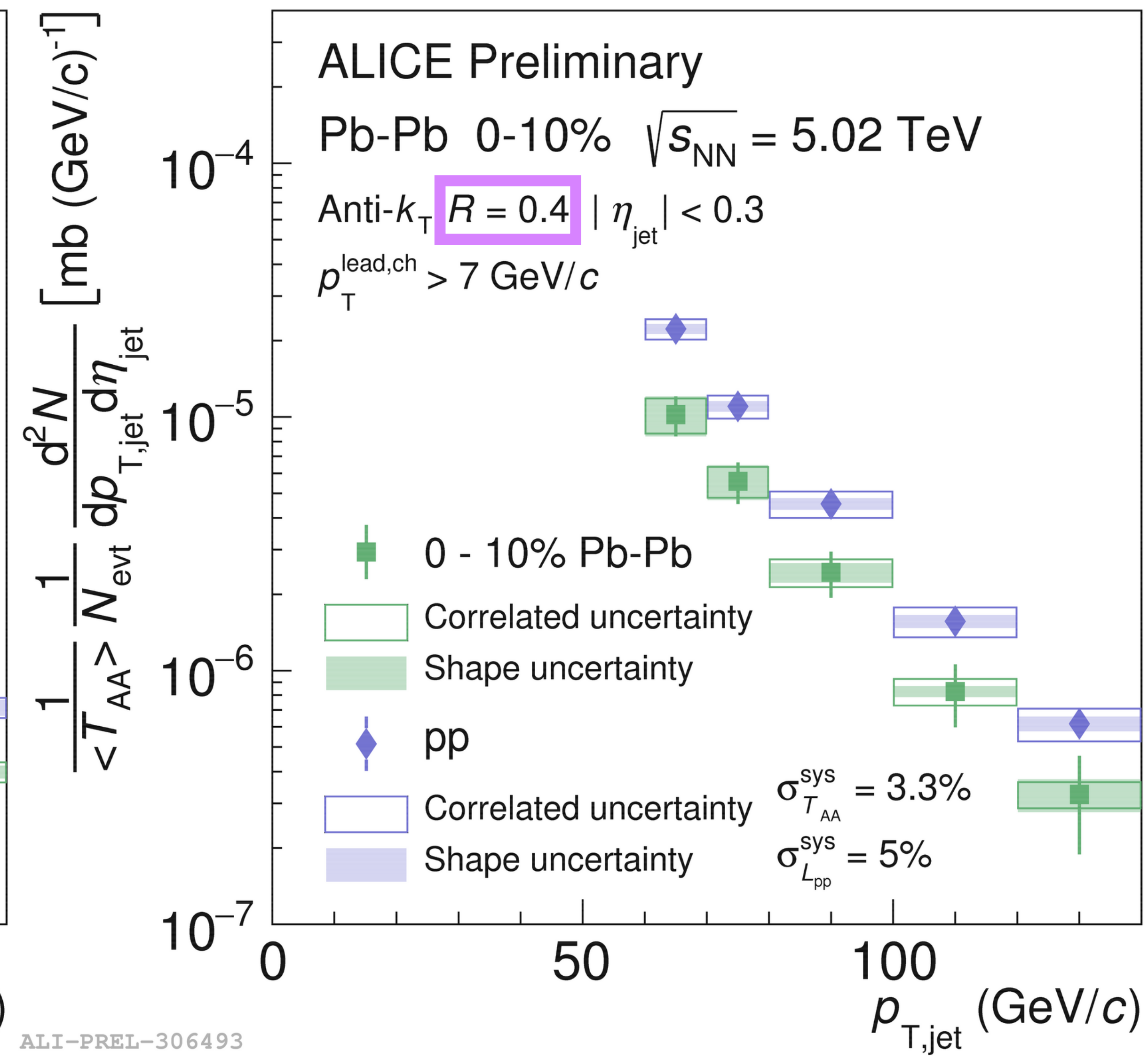


Measurements consistent with POWHEG + Pythia8

Jet cross-section: 0-10% Pb + Pb collisions

$40 < p_{T,Jet} < 140$ GeV/c Jet reconstruction w/ Anti-k_T; cone sizes: 0.2, 0.4

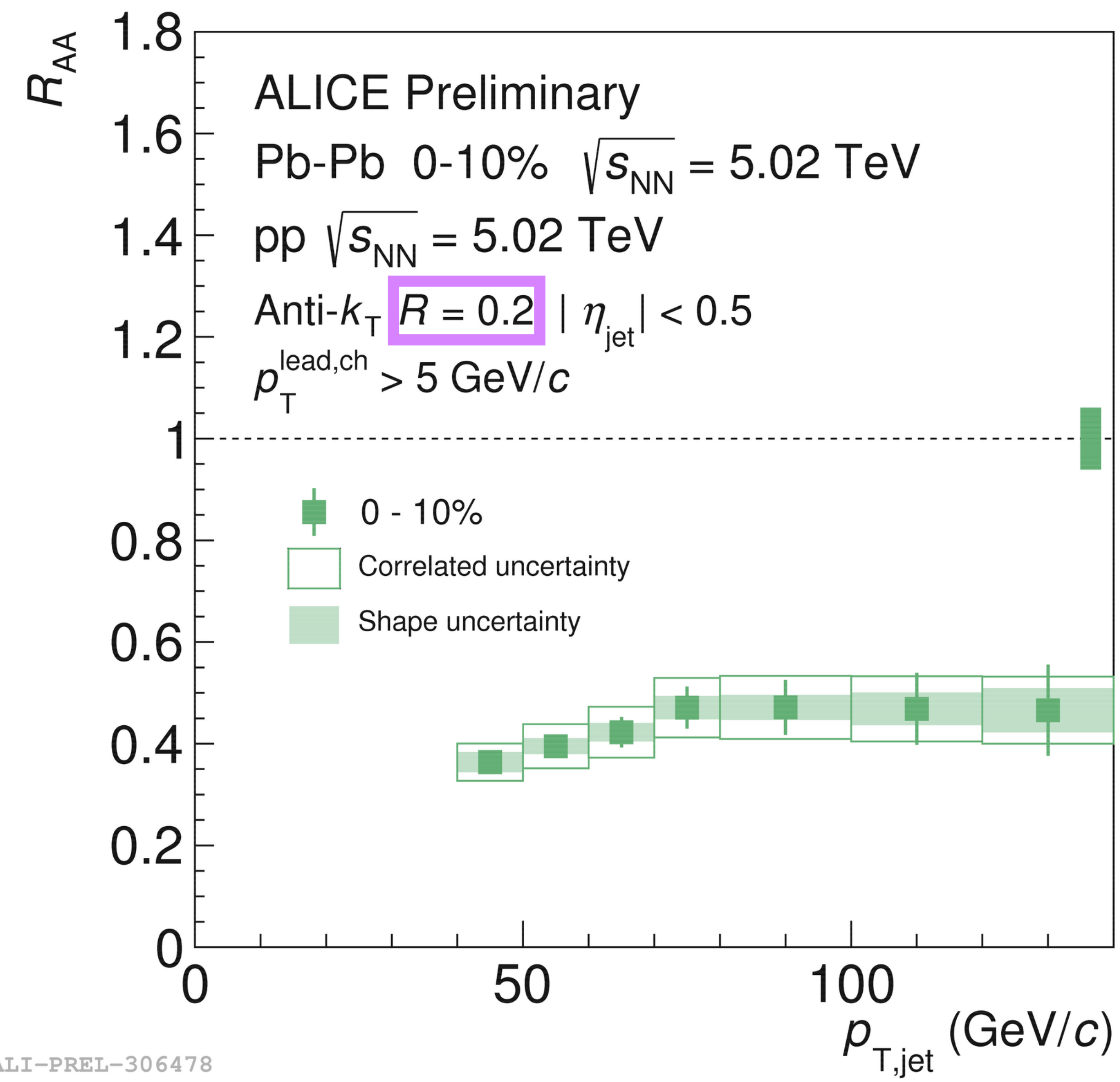


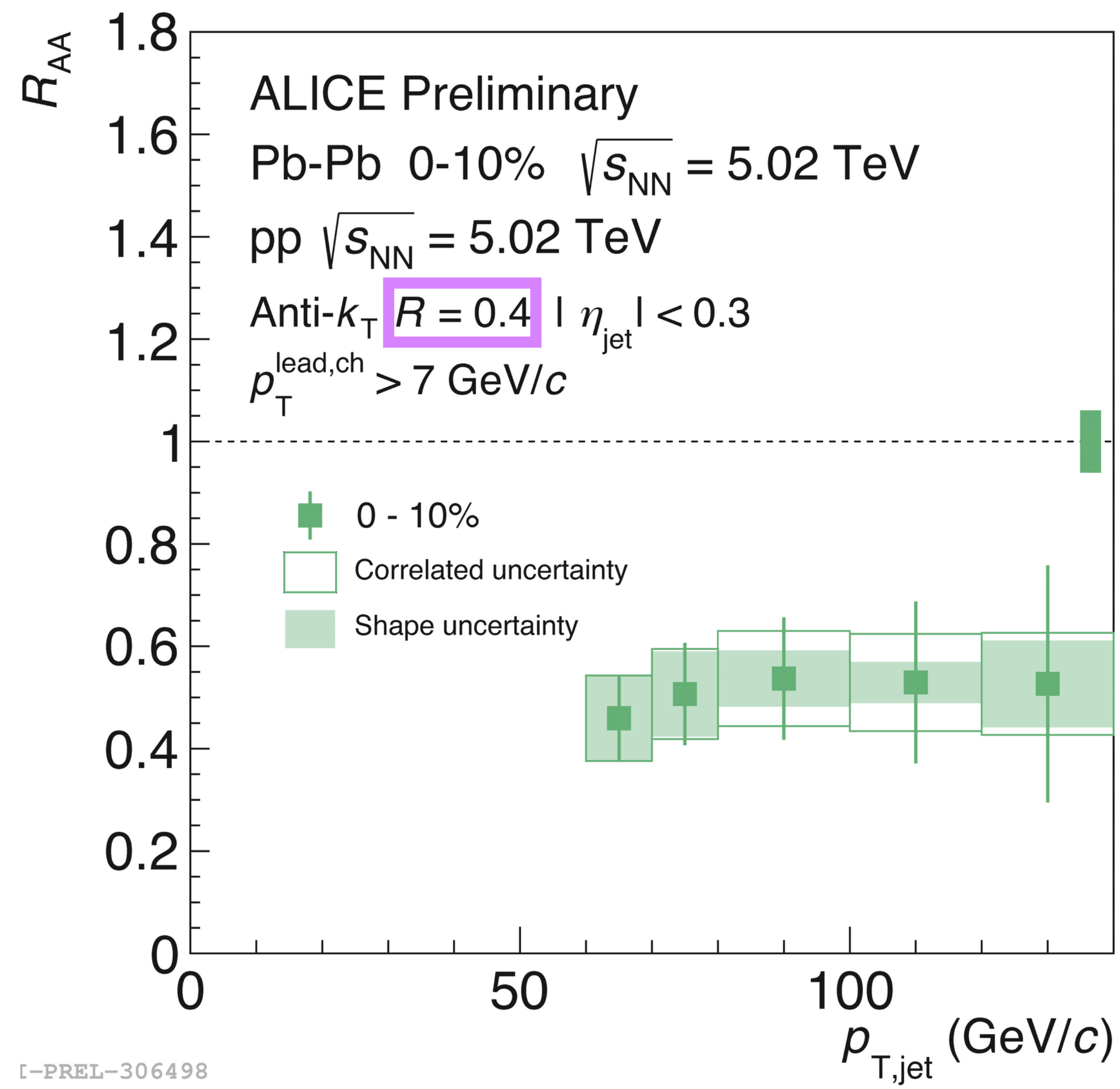


First full jet measurement at $p_{T,jet} < 100$ GeV/c at 5.02 TeV

Jet R_{AA}

R_{AA} Definition: $$R_{AB}(p_t) = \frac{d\sigma_{AB}/dyd^2p_t}{\langle N_{bin}\rangle d\sigma_{NN}/dyd^2p_t}$$

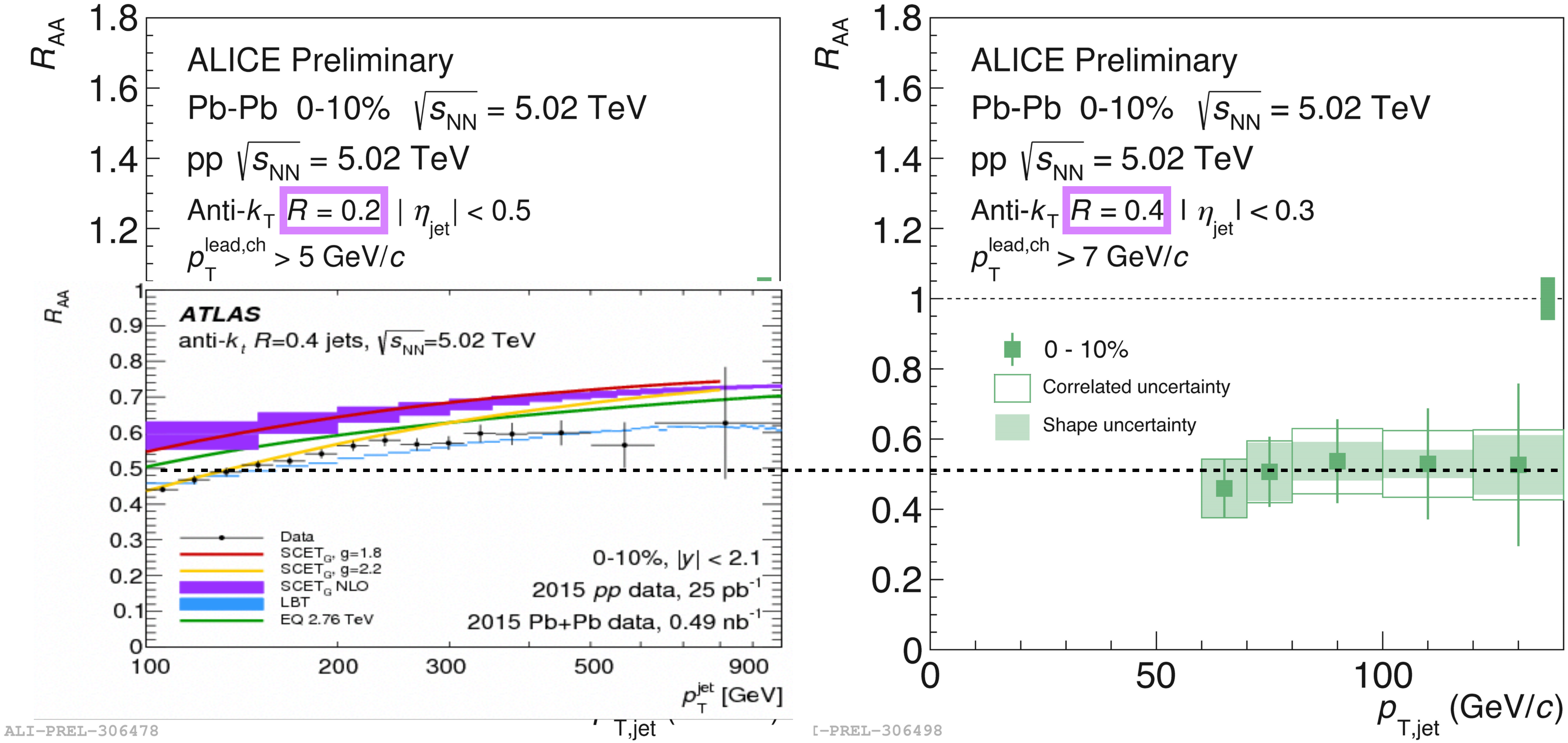




Similar suppression observed in R=0.2 and R=0.4

Jet R_{AA}

R_{AA} Definition: $$R_{AB}(p_t) = \frac{d\sigma_{AB}/dyd^2p_t}{\langle N_{bin}\rangle d\sigma_{NN}/dyd^2p_t}$$



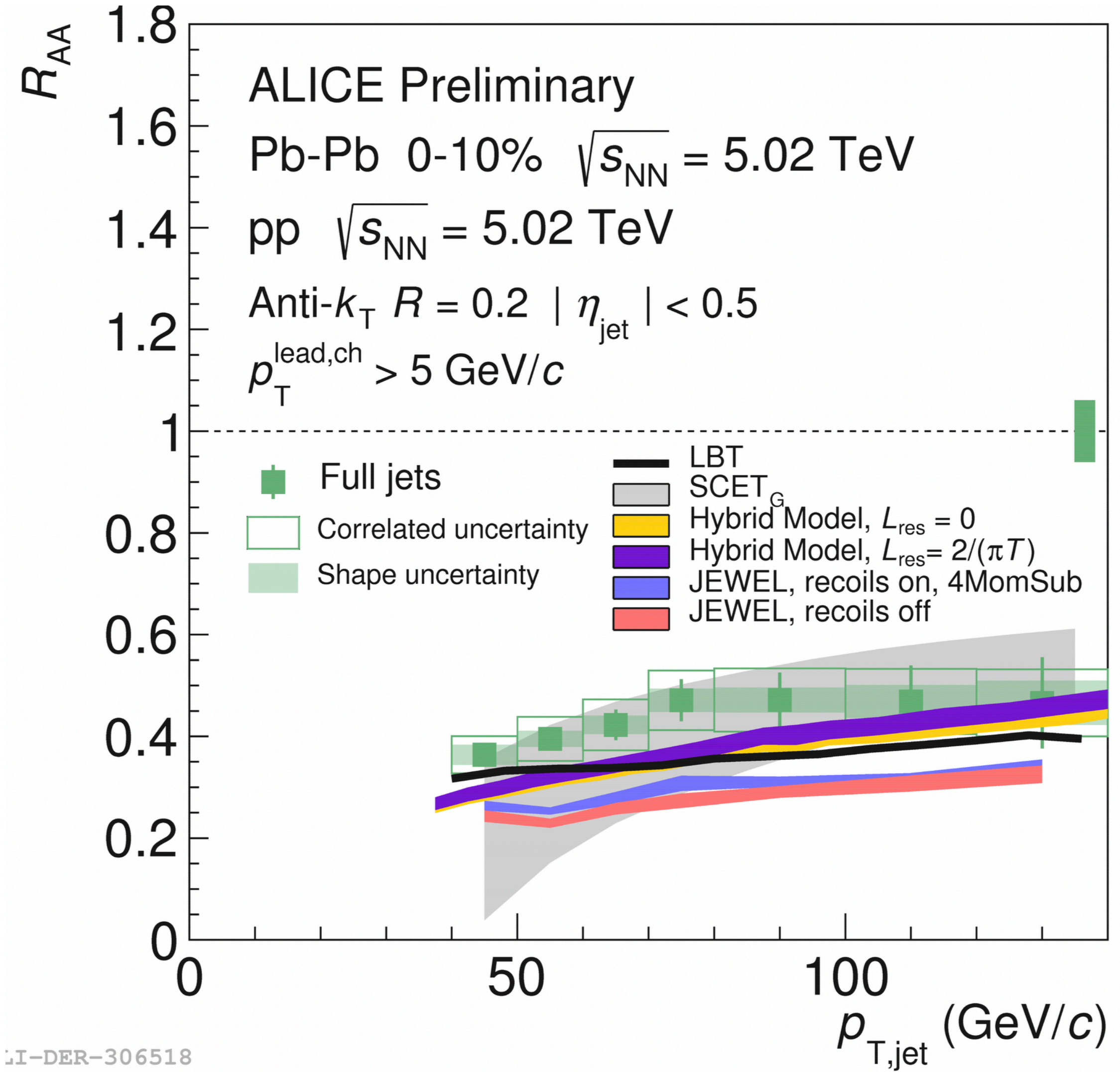
Similar suppression observed in R=0.2 and R=0.4

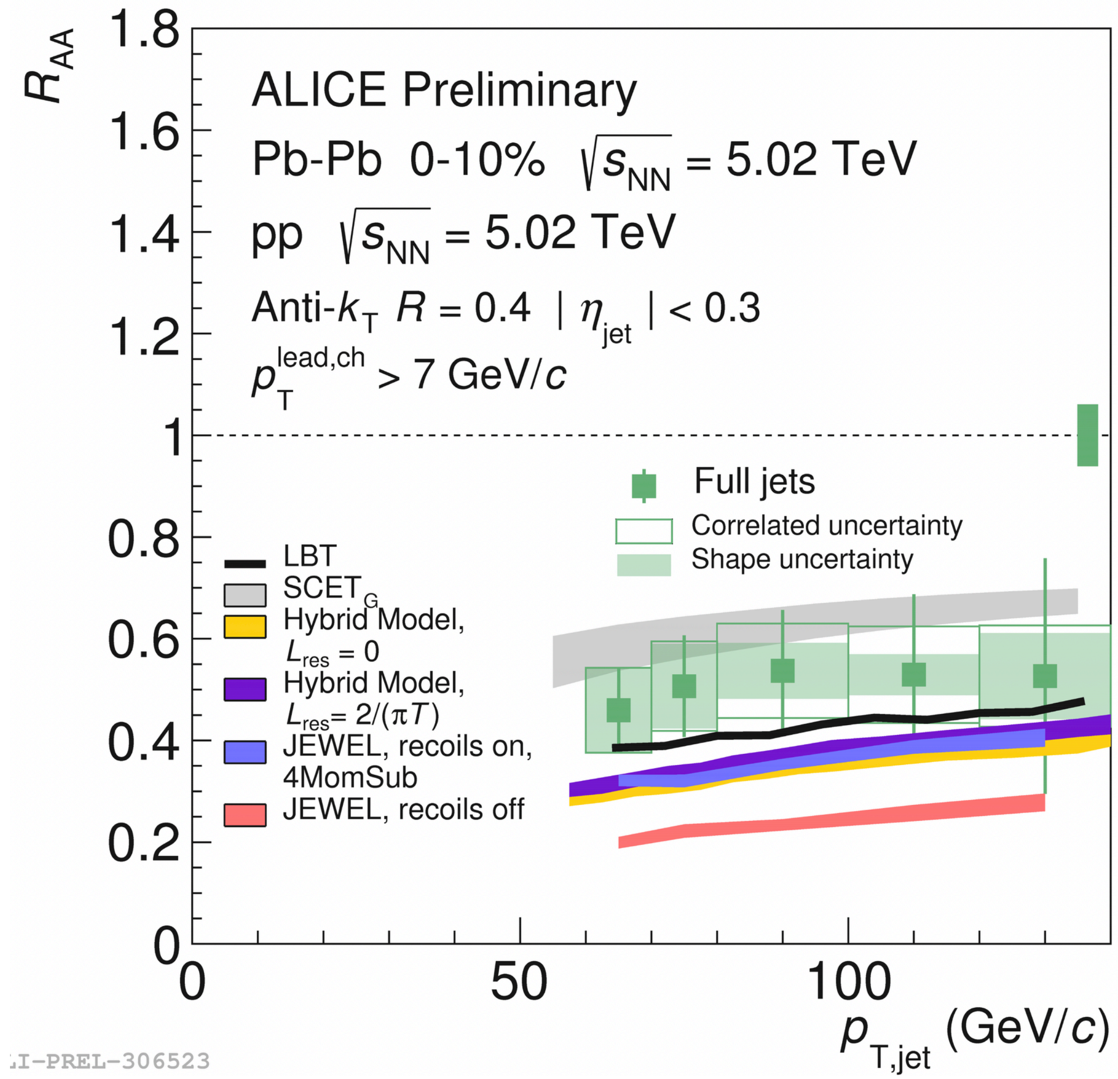
Consistent with ATLAS R=0.4 jet R_{AA}

Also verified that full jet R_{AA} consistent w/ Charged jet RAA (backup slides)

Full Jet R_{AA}

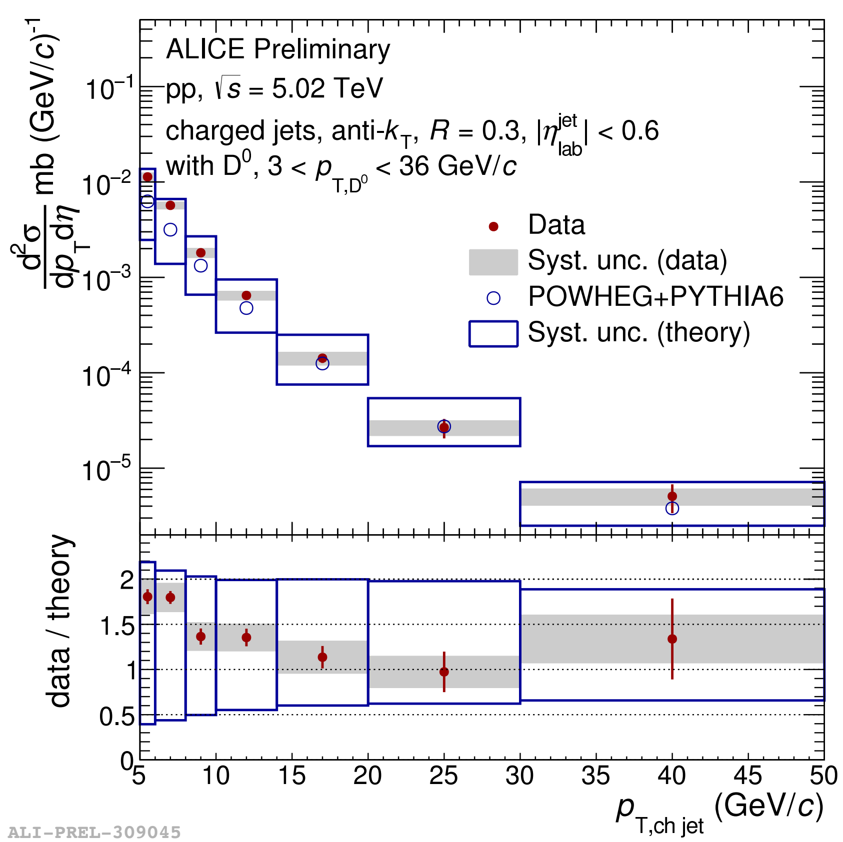
R_{AA} Definition: $R_{AB}(p_t) = \frac{d\sigma_{AB}/dyd^2p_t}{\langle N_{bin}\rangle d\sigma_{NN}/dyd^2p_t}$

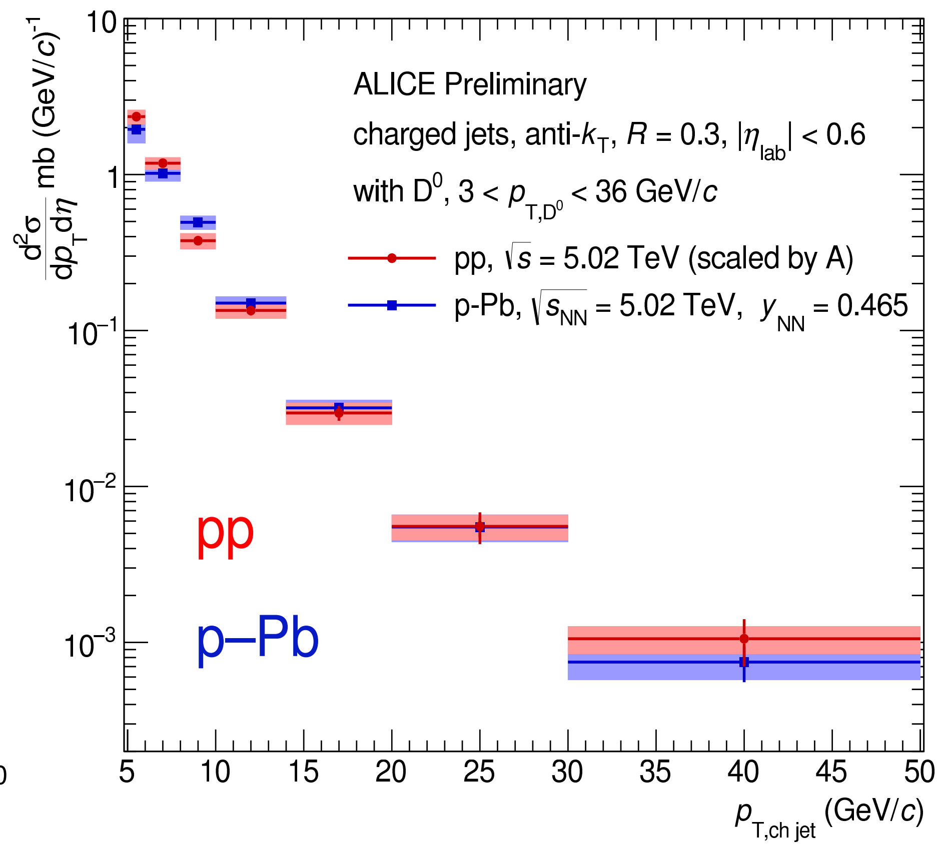


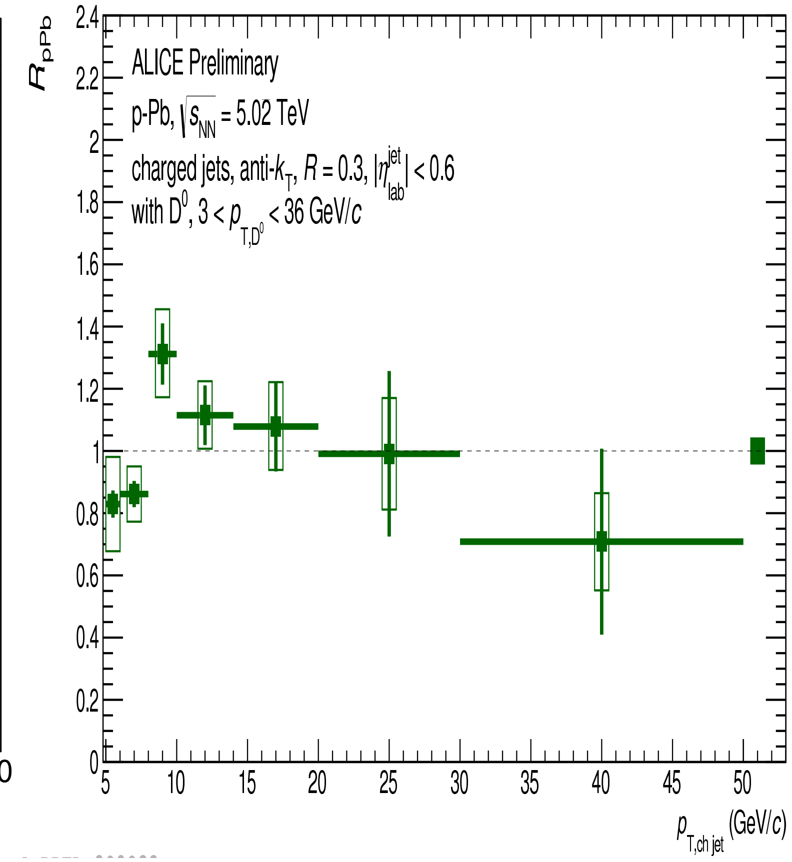


All models qualitatively describe the measured R_{AA}
But tension with the data remain for most models.

D^0 Jets in pp, p+Pb at $\sqrt{s}$ = 5.02 TeV







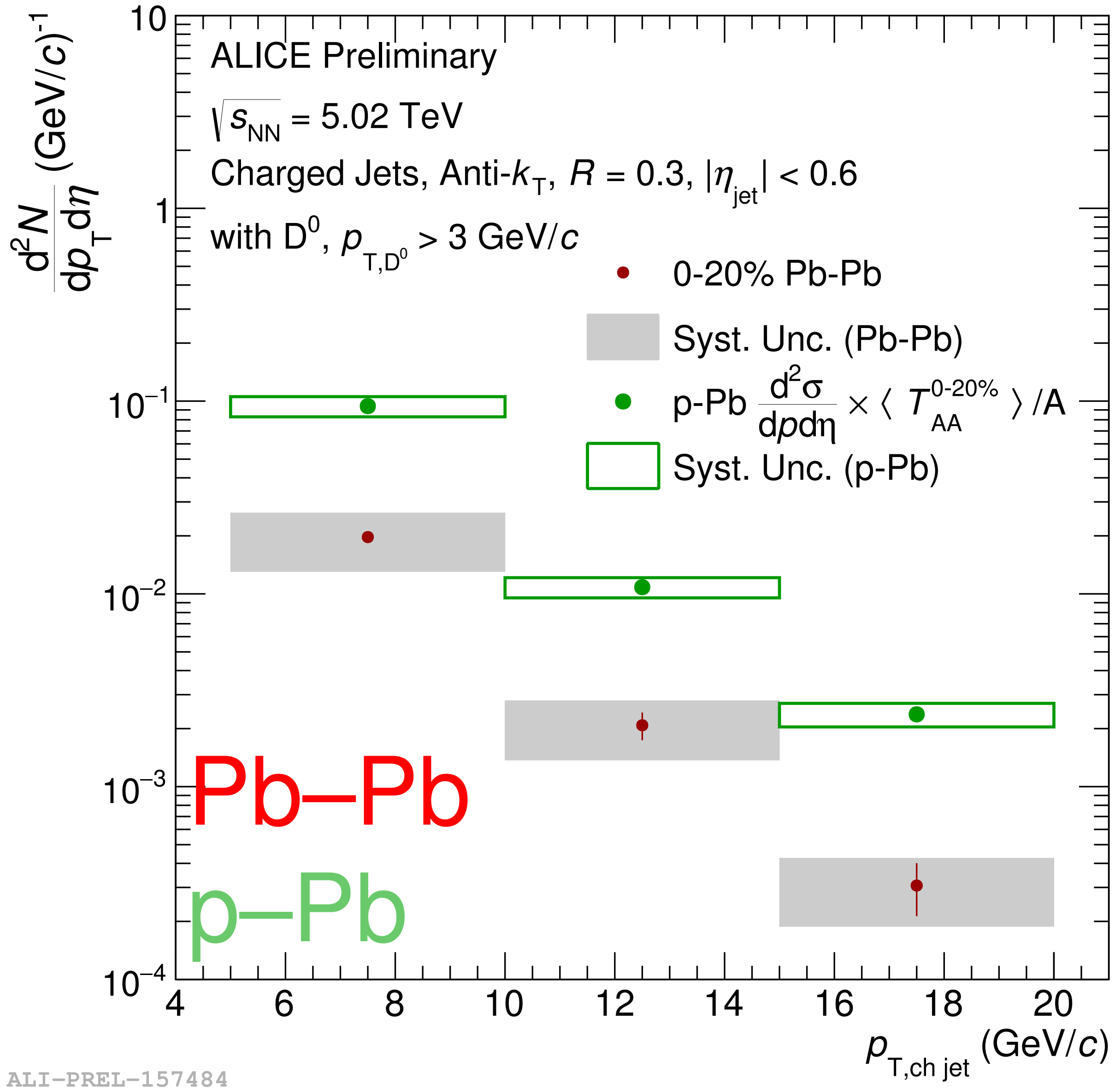
$R_{\mathrm{pPb}} \approx 1$ within uncertainties

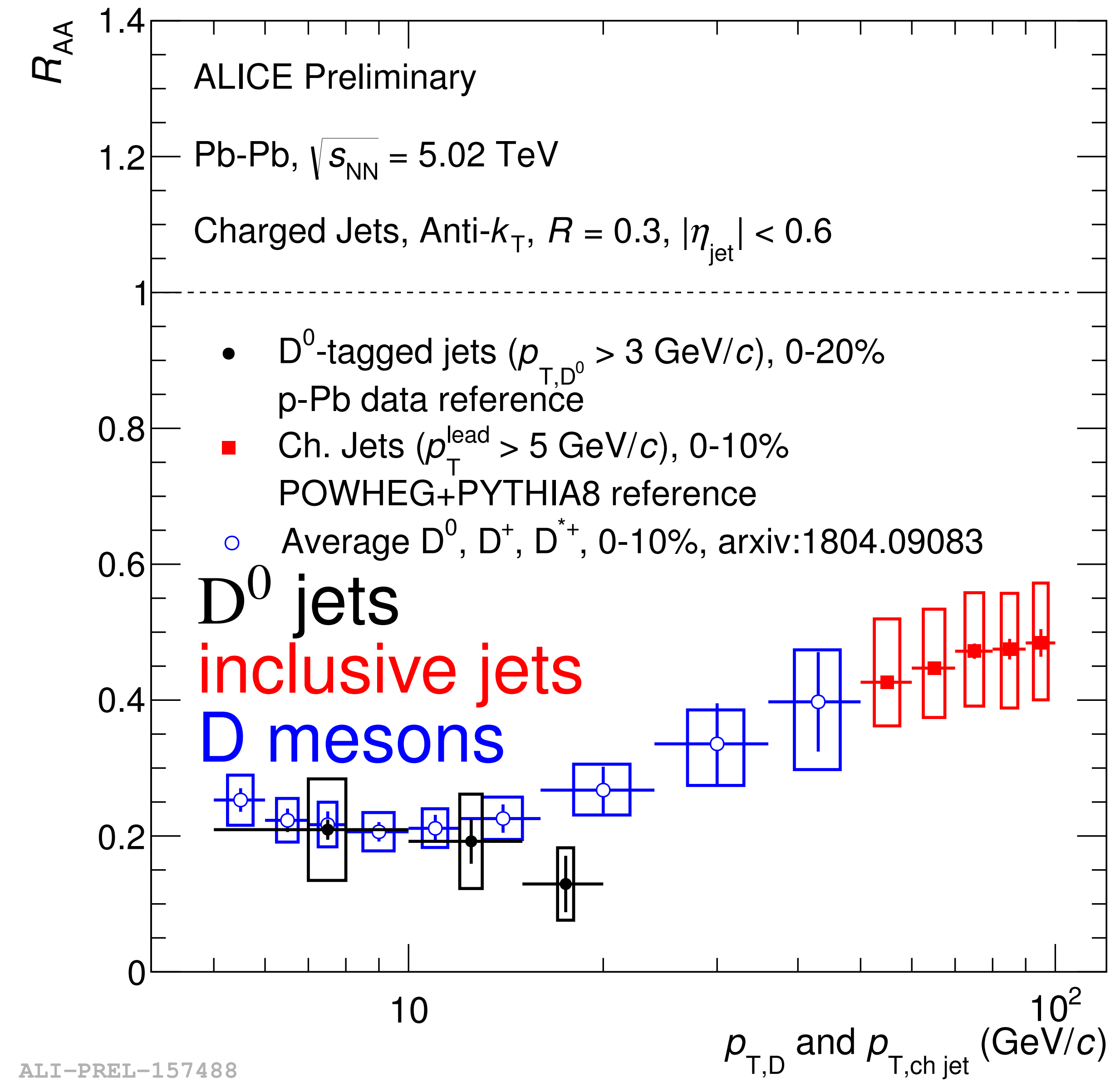
No evidence for jet suppression in p-Pb

D^0 Jet Reconstruction

- D^0 Meson
  - Decay channel: $D^0 \to K^-\pi^+$, BR = 3.89% [PDG PRD 98 (2018) 030001]
  - TPC dE/dx + TOF PID for K/π discrimination
  - Topological selections (secondary vertex)
  - $p_{\mathrm{T,D}} > 3$ GeV/c
- Jet finding
  - D^0-meson candidates replace the decay products in the jet finding
  - Track-based
  - anti-k_{T}, $R = 0.3, 0.4$
  - $p_{\mathrm{T,ch\,jet}} > 5$ GeV/c

R_{AA} of D0-Meson Jets in Pb–Pb at √sNN = 5.02 TeV





D0-Jet RAA ~ 0.2 in 5 < pT,ch-jet < 20 GeV/c
Similar to D meson (non-photonic electrons) and inclusive jets.

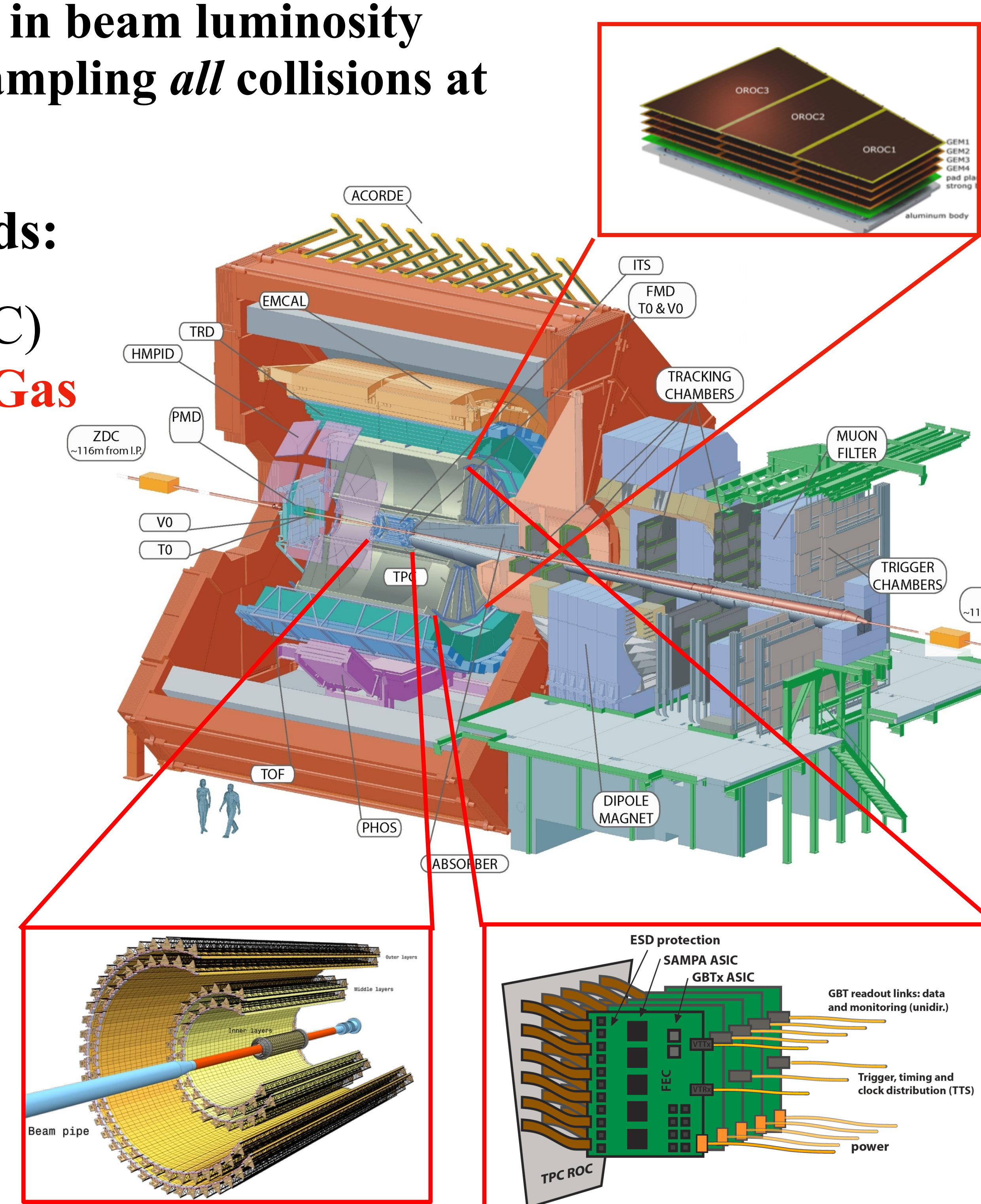
ALICE Barrel Tracking Upgrade -

Upcoming LHC Run-3 will see **factor 10+ increase in beam luminosity**
ALICE will operate in continuous read-out mode, **sampling *all* collisions at 50 kHz**

ALICE-USA institutions collaborating towards:

- New TPC "**Inner Readout Chambers**" (IROC)
  - Build 40 + spares stacks of high-precision **Gas Electron Multiplier (GEM)** chambers
- New **TPC read-out electronics** based on the **'SAMPA' chip**
- New "Inner Tracking System" w/
  - 10 m² of silicon, 12.5 Gigapixels
  - middle layers and readout electronics

WAYNE STATE Physics and Astronomy
OAK RIDGE National Laboratory
TEXAS The University of Texas at Austin
Yale
BERKELEY LAB



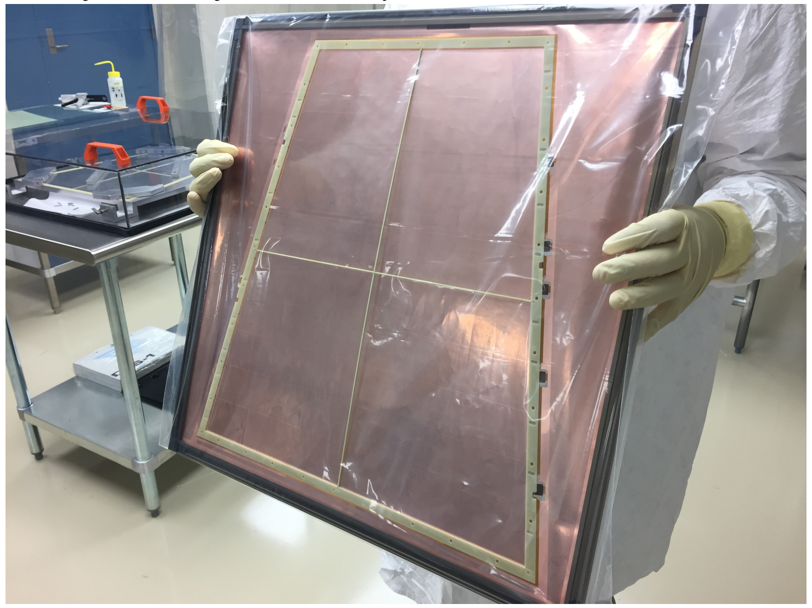
Inner Tracking System (ITS)

Time Projection Chamber: Inner Readout Chambers (IROC)

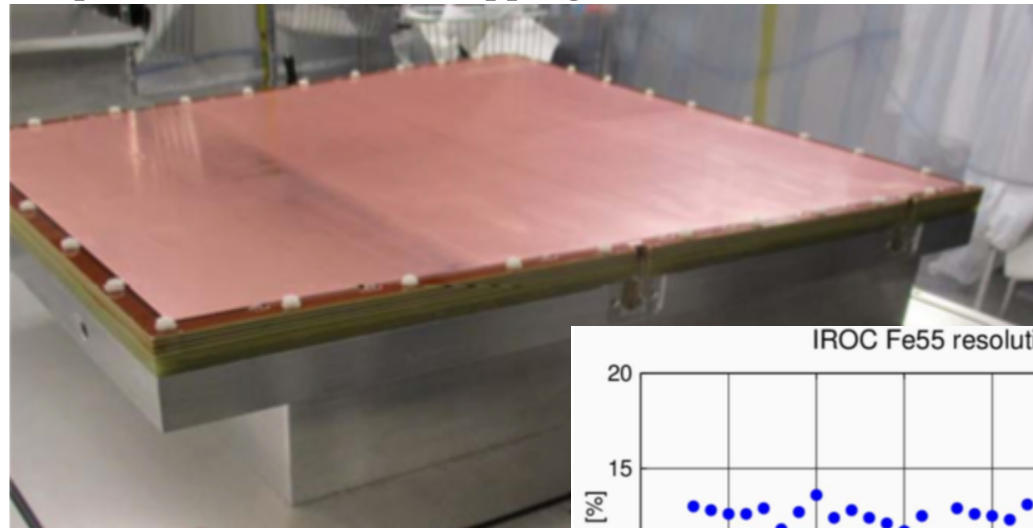
Construction of all IROC chambers complete in ~2 months
Entire project complete in less than 1 year.

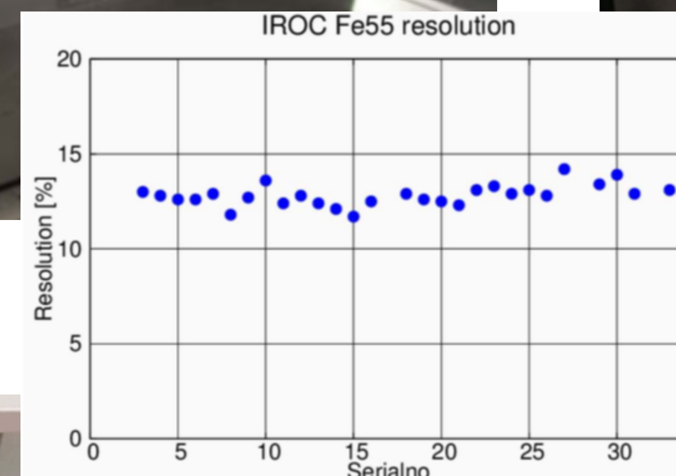
IROC "Alubody" at UT-Austin

First framed foil at Wayne State



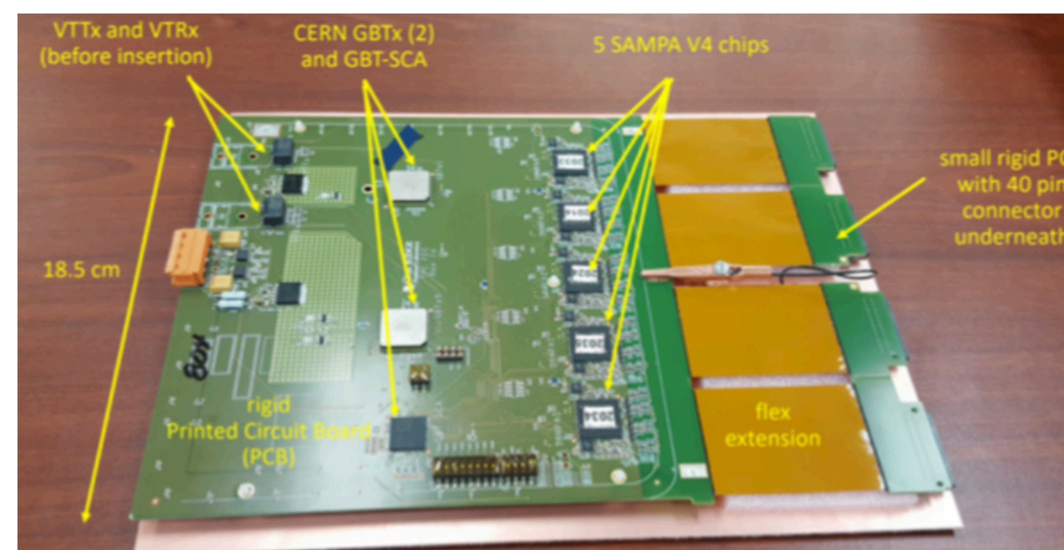
Complete IROC in test & shipping vessel at Yale





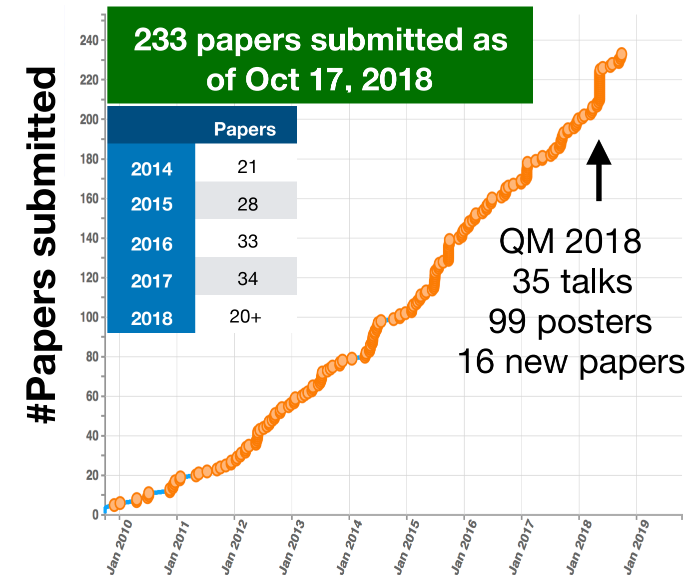
Complete half-barrel of ITS

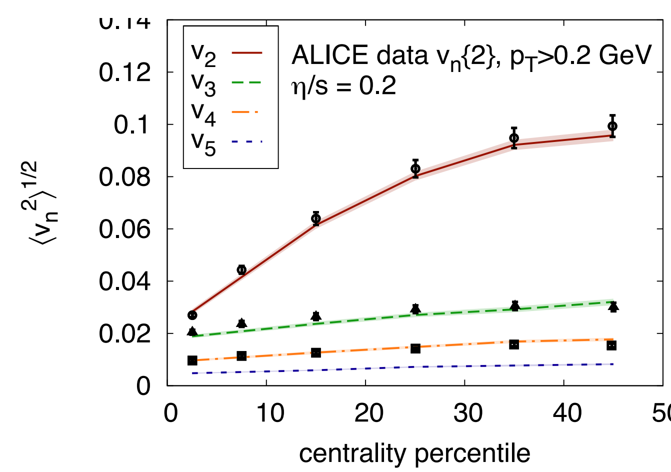
New TPC FEE at UT-Knoxville

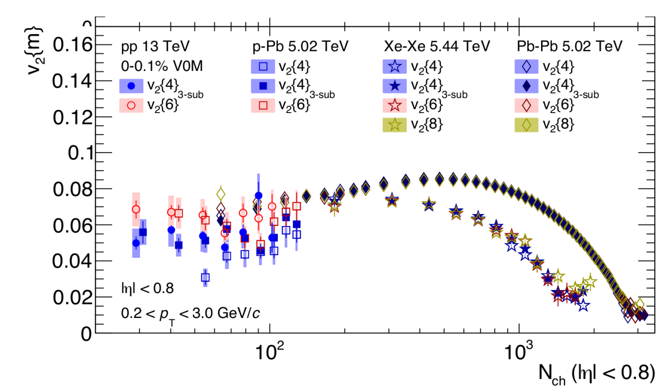


Summary

- **A wealth of results…**
  - 4 collisions systems; several beam energies
  - 233 papers as of Oct 17, 2018
  - ~ 30 papers/annum
  - 100s of conference contributions/annum
- **Homing in on some properties of the QGP**
  - Initial state conditions
  - Shear viscosity
  - Hadro-chemistry
  - Transport coefficients
- **Increasing evidence of collective behavior in large multiplicity p+p and p+Pb collisions** but origin of behavior (initial/final state) still debated.
- Much more to come w/ Run 2 and w/ Run 3 ALICE upgrade…



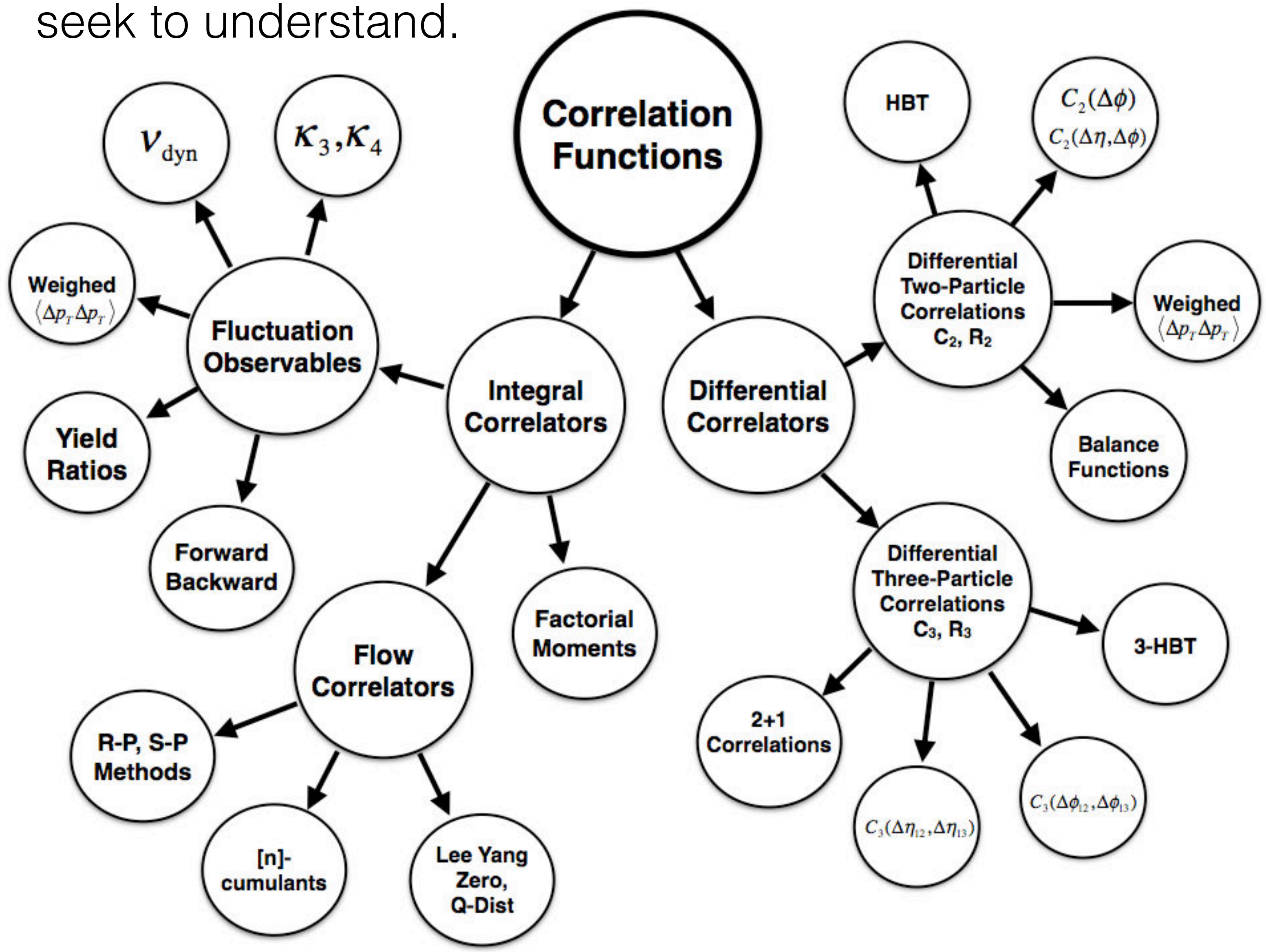




Learn more about correlation functions here….

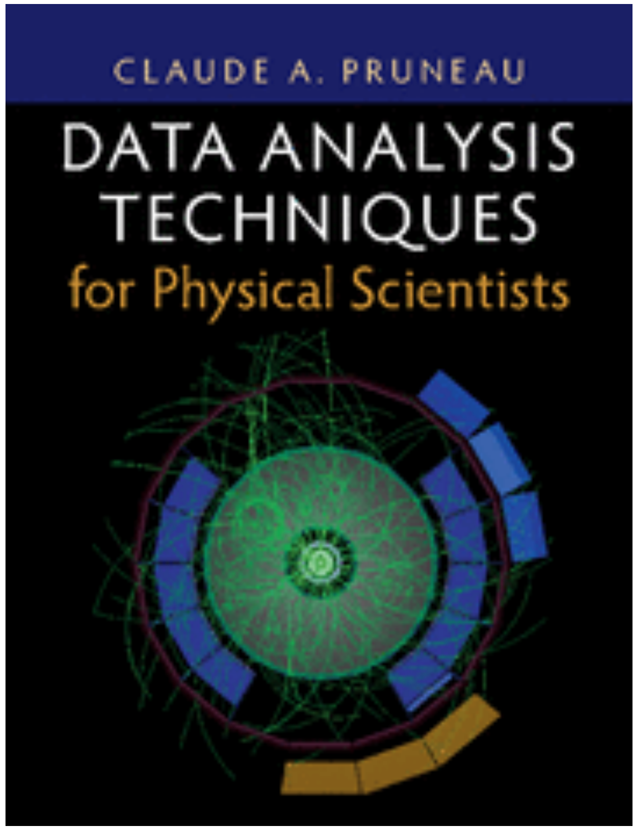
A shameless plug…

- A large fraction of measurements in Heavy Ion are based on **correlation observables**.
- Correlation observables are all inter-connected.
- They measure/emphasize different aspects of the physics we seek to understand.



For basic intro, see:

www.cambridge.org/9781108416788



Topics	#Chapters
Classical Statistics	5
Bayesian Statistics	1
Data Reconstruction/ Analysis Methods	2
Correlation Functions	2
Data Correction/Unfolding	1
Basic Monte Carlo Techniques	2

Available on amazon.com